The Fermi Large Area Telescope, Astrophysics, Dark Matter Searches and the 130GeV Line

Eric Charles
on Behalf of the Fermi-LAT Collaboration

Fermilab, 2013 April 8

Outline

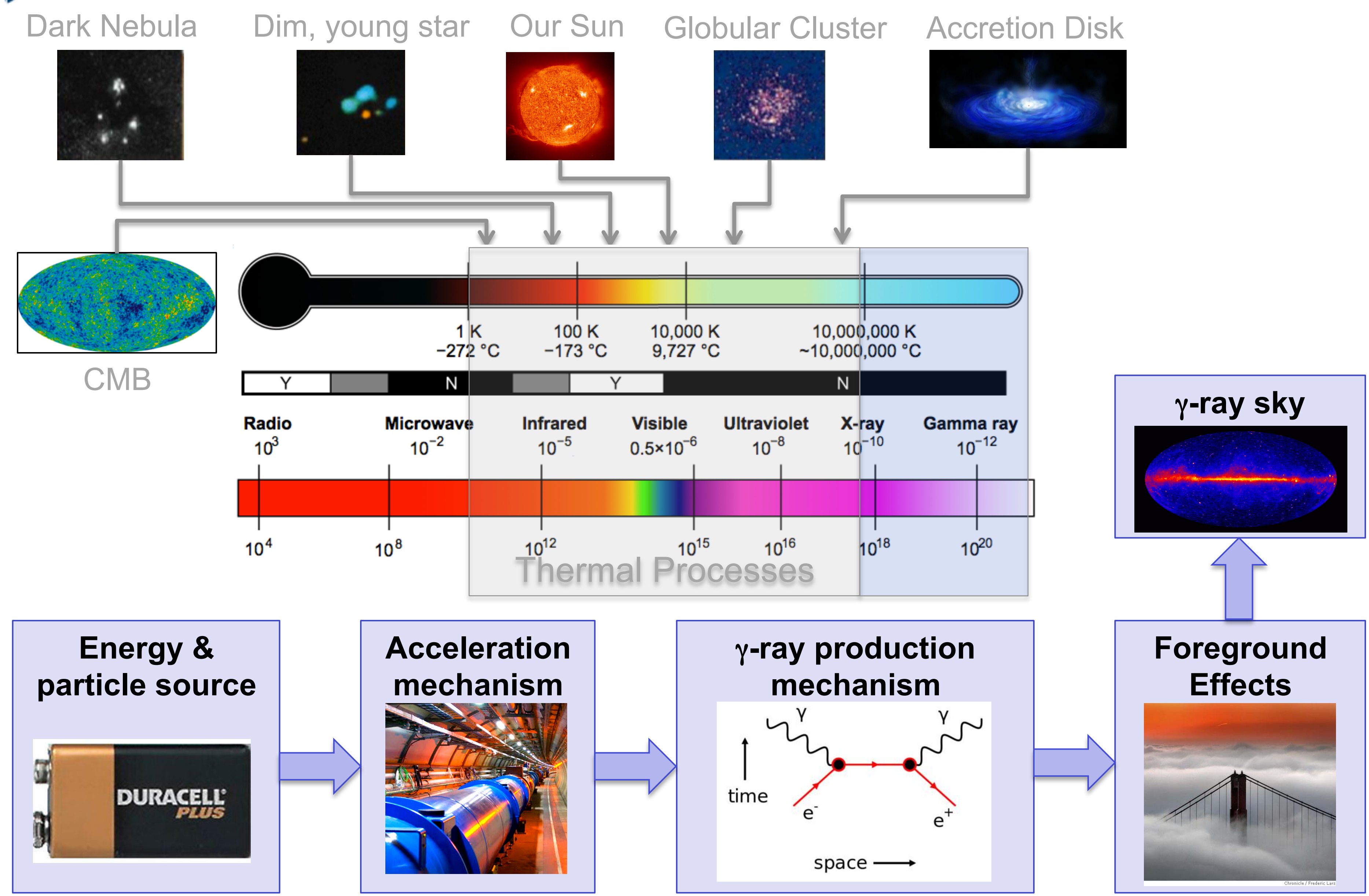
γ-ray Astronomy and the Fermi-LAT
- Considerations for Data Analysis
- Recent Scientific Highlights

Indirect Searches for Dark Matter
- Fermi-LAT Search Strategies
- Overview of Results

Narrow Spectral Line at 130 GeV
- Context: Results from Weniger and Su & Finkbeiner
- Fermi-LAT line search

γ-RAY ASTRONOMY AND THE FERMI-LAT

γ-rays Probe the Extreme, Non-Thermal, Universe



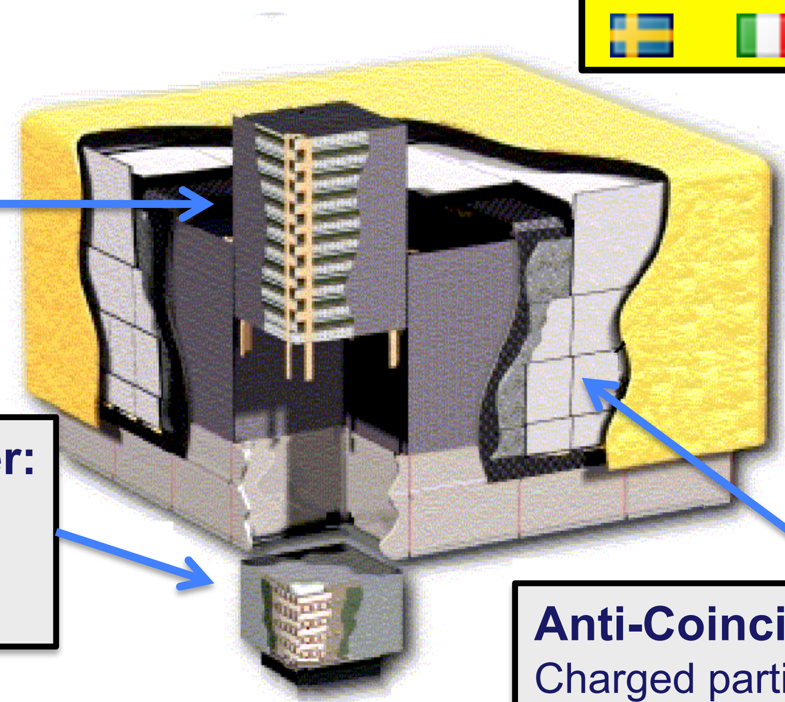
Considerations for Data Analysis

The Fermi Large Area Telescope

Public Data Release:
All γ-ray data made public
within 24 hours (usually less)

Fermi LAT Collaboration:
~400 Scientific Members,
NASA / DOE & International
Contributions

Si-Strip Tracker:
convert $\gamma \to e^+e^-$
reconstruct γ direction
EM v. hadron separation



Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

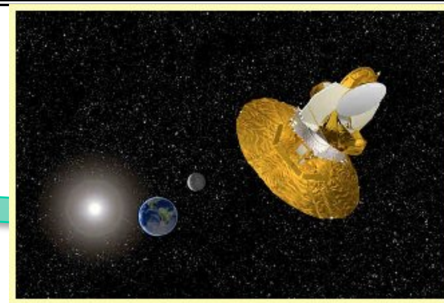
Anti-Coincidence Detector:
Charged particle separation

Sky Survey:
With 2.5 sr Field-of-view LAT
sees whole sky every 3 hours

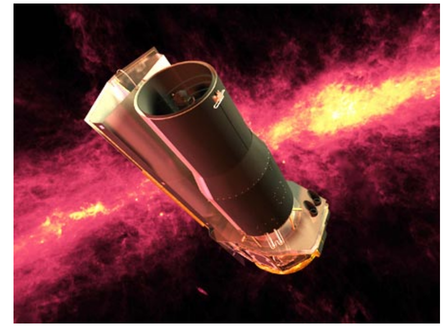
Trigger and Filter:
Reduce data rate from ~10kHz
to 300-500 HZ

Synergy with Other Instruments

Radio: pulsations, synchrotron emission, ISM maps,
high resolution imaging of jets
AGN host galaxies…



Microwave: diffuse maps & morphology, Galaxy characteristics…

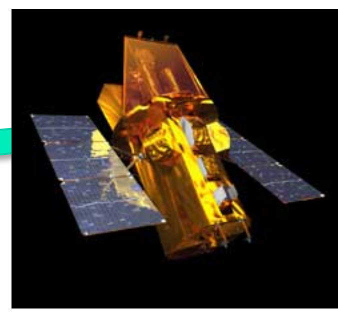


IR: ISM maps, AGN/GRB host galaxies…

LAT Source Localization ~0.1°--0.01° comparable to many field-of-views
LAT: 4+ decades energy band provides lever-arm for spectral fits

Energy

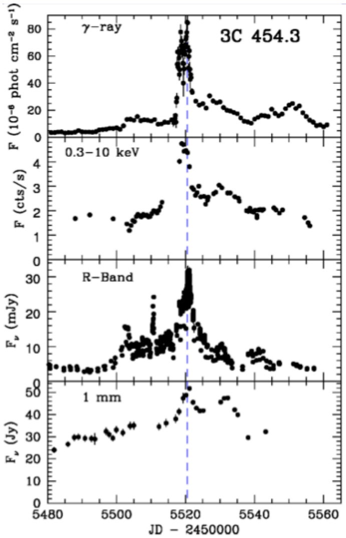
TeV: High-energy spectral breaks, SNR/PWN morphology…



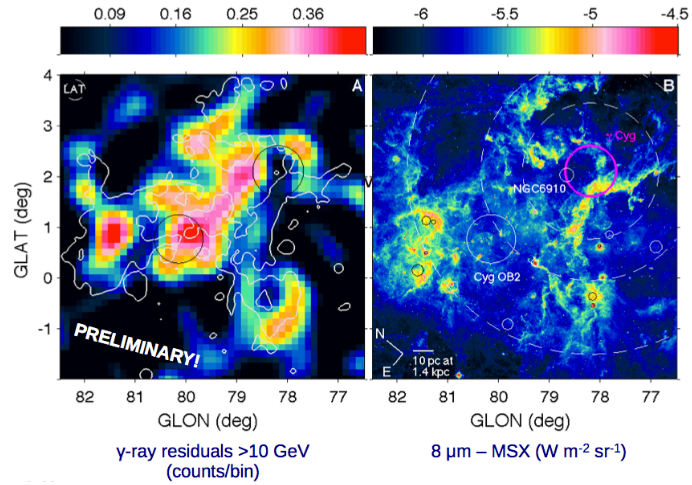
X-ray:
GRB & Flare afterglows,
morphology & pulsar association…

Optical:
GRB afterglows,
AGN/GRB redshifts

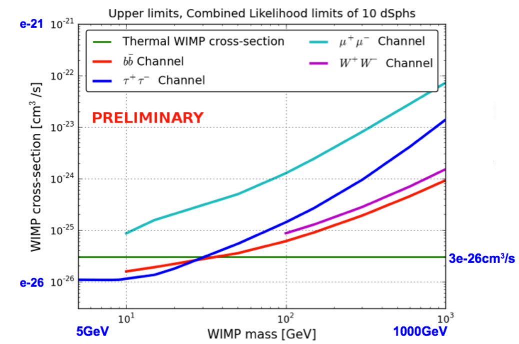
Wide Variety of Analysis Subjects



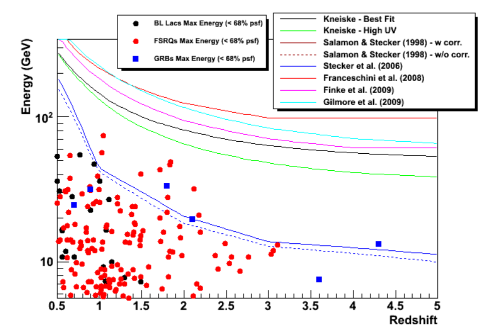
MW Variability



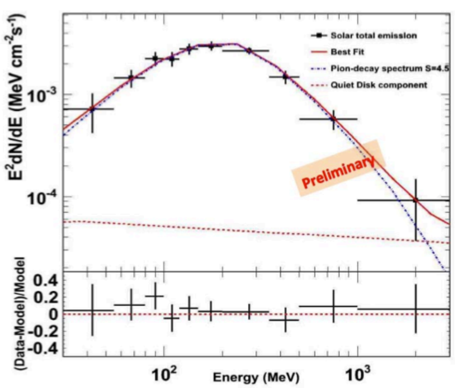
Morphology, Source Extension and Counterpart Identification



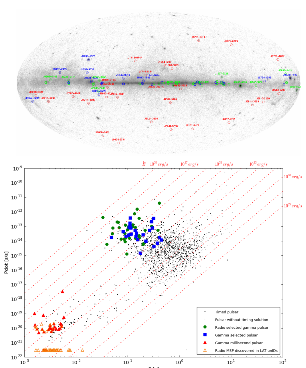
DM Searches

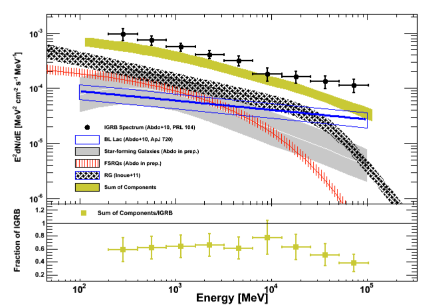


Single Photon Studies



SEDs and Spectral Components

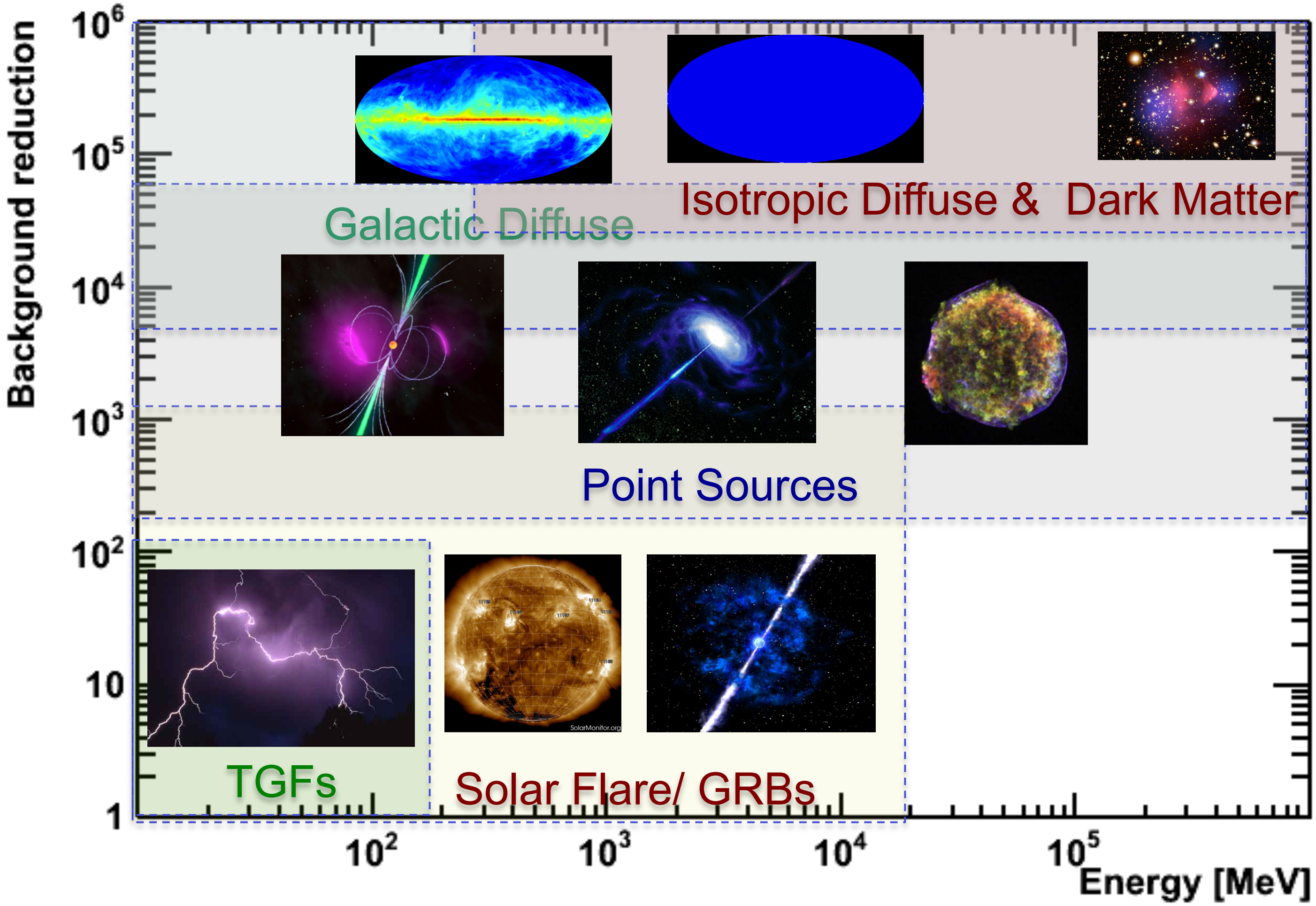




Catalogs, Population Studies and Contribution Estimation

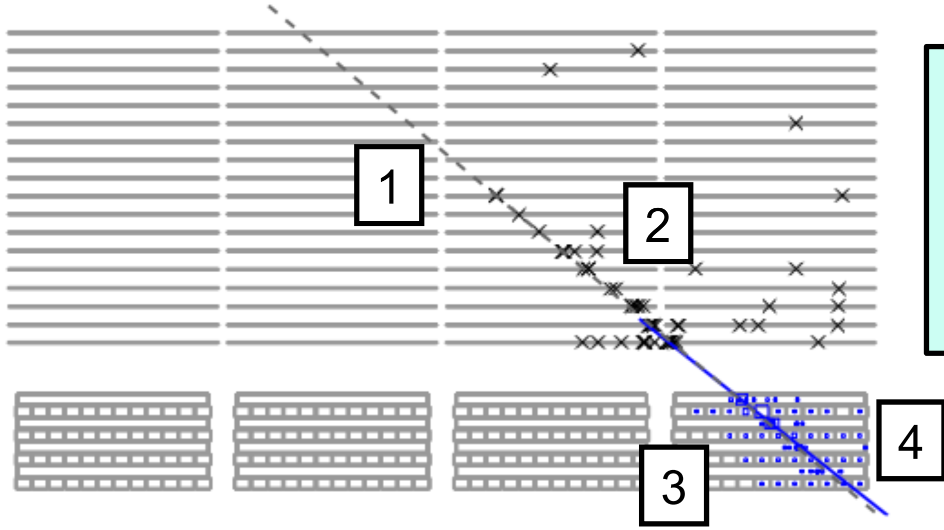
No real "standard" analysis
Many particulars

Fermi-LAT Science Covers Huge Phase-Space



Different data selections for different science cases

LAT Detects Individual γ rays (and Cosmic Rays)

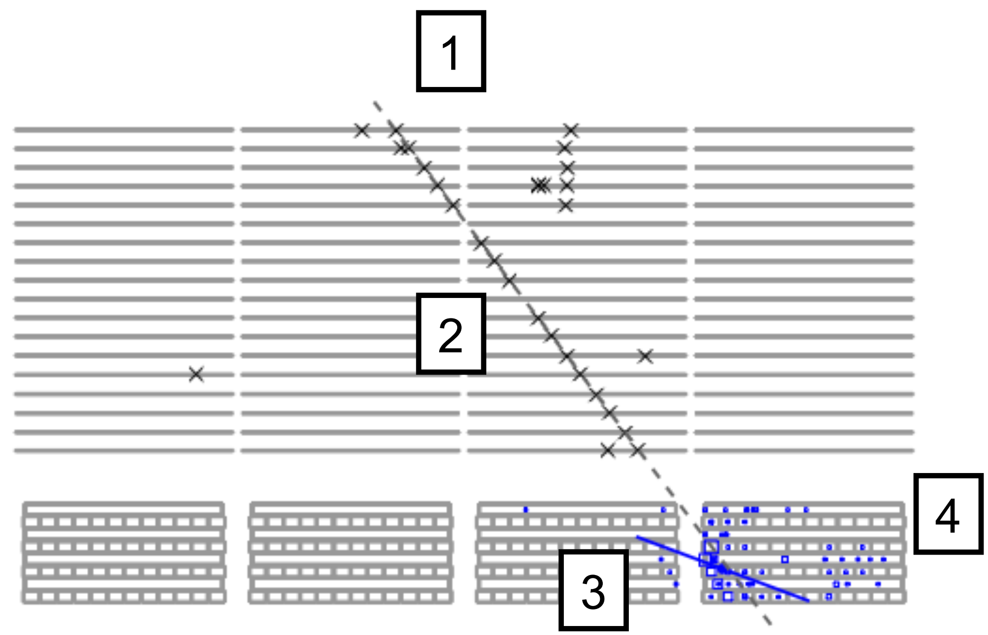


Nearly ideal γ-ray candidate:

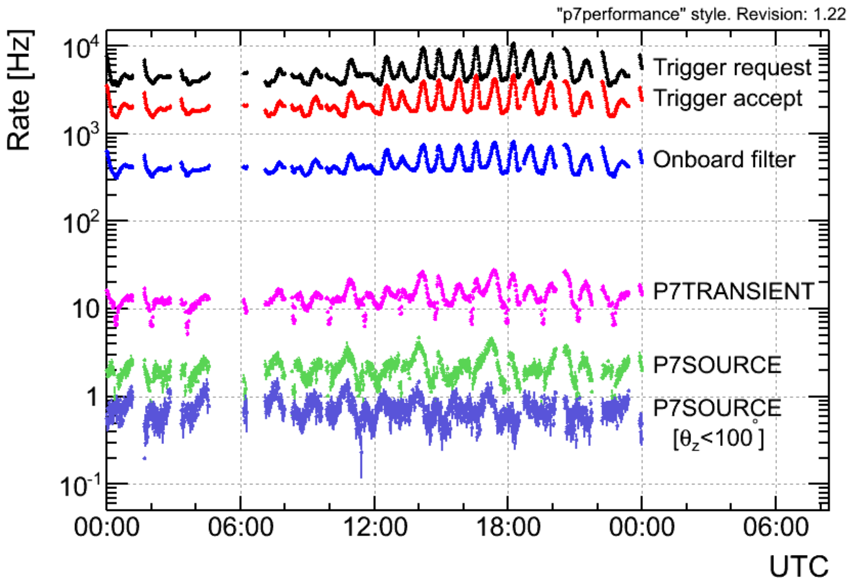
1. Starts in middle of TKR
2. Extra hits near track
3. CAL axis aligned with track
4. CAL energy confined near axis

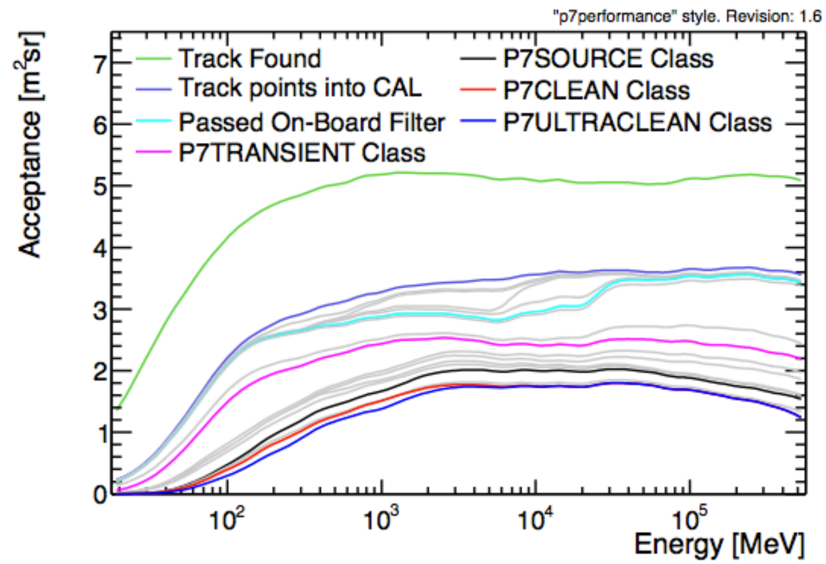
Nearly ideal proton candidate:

1. Starts at top of TKR
2. Few extra hits near track
3. CAL axis not-aligned with track
4. CAL energy “lumpier”
5. Signal in the ACD (not shown)



Particle Rate Reduction





Ackermann et al.: [2012ApJS..203....4A]

Factor of > 10^5 in bkg. reduction is achieved in several stages

About 50% γ-ray efficiency inside fiducial volume from 1-100 GeV

Instrument Response Functions

Measured Energy & Direction

Effective Area

Energy Dispersion

$$R(E',\hat{v}';E,\hat{v}) = A_{eff}(E,\hat{v})P(\hat{v}';E,\hat{v})D(E';E,\hat{v})$$

Point-spread Function

True Energy & Direction

Expected Count Rate

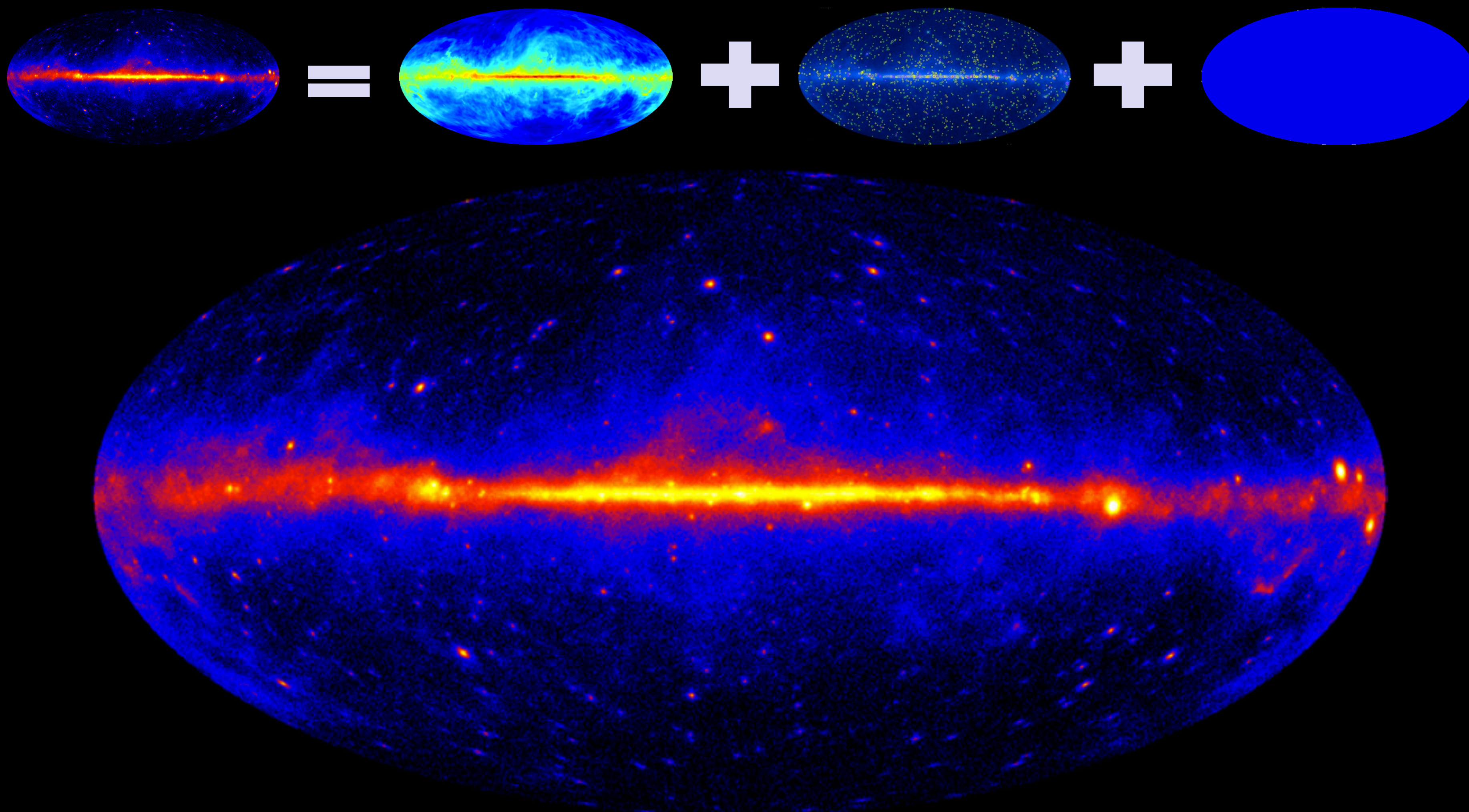
Source Flux

$$\frac{dM(E',\hat{v}')}{dt} = \int\int R(E',\hat{v}';E,\hat{v})F(E,\hat{v})d\hat{v}dE$$

Instrument Response

Likelihood fitting uses lots of information optimally.
This is a double-edged sword. Issues with any of our IRFs can affect fit and can be difficult to disentangle.

Decomposing the GeV Sky



Likelihood Fitting

Expected counts from sum of flux models

$$M_{tot}(E', \hat{v}') = M_{gal}(E', \hat{v}') + M_{iso}(E', \hat{v}') + \Sigma^{src} M_{src}(E', \hat{v}')$$

Poisson prob. to see n given M expected

$$P(n; M) = \frac{M^n}{n!} e^{-M}$$

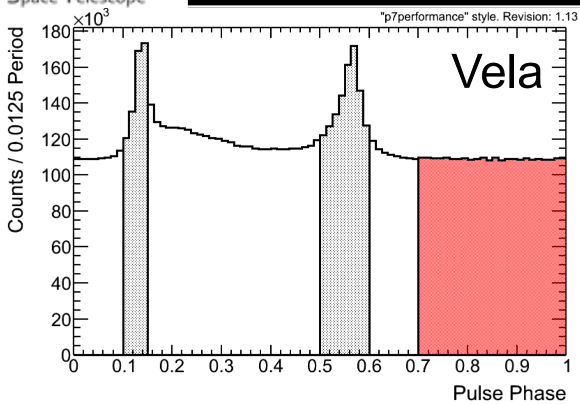
Log likelihood (binned fit)

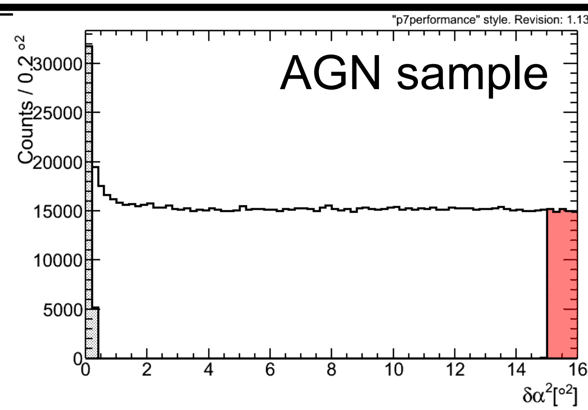
$$\mathcal{L} = \log \Pi_i^{bin} P(n_i; M_i)$$

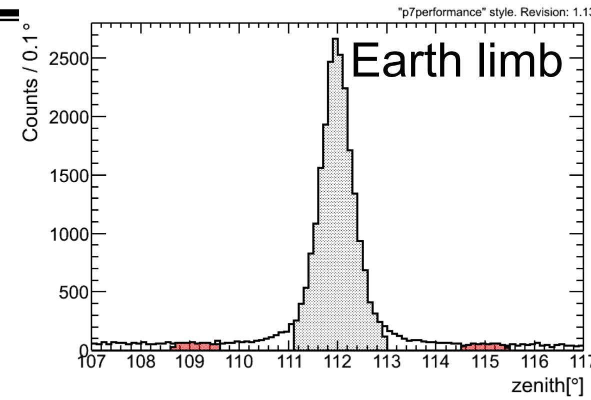
Likelihood fitting is a *hypothesis testing* tool

It can only tell you about what you put into the model, and everything you observe has to be accounted for by some aspect of the model

Flight Data Calibration Samples

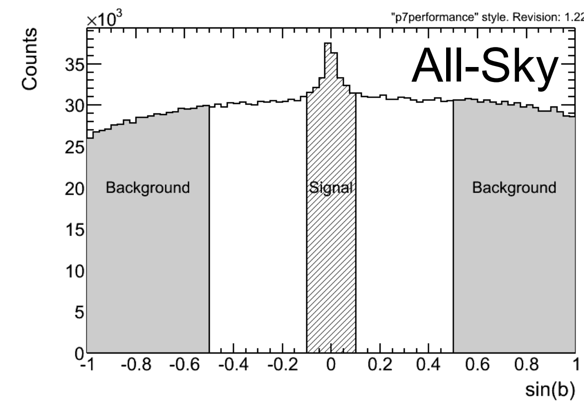


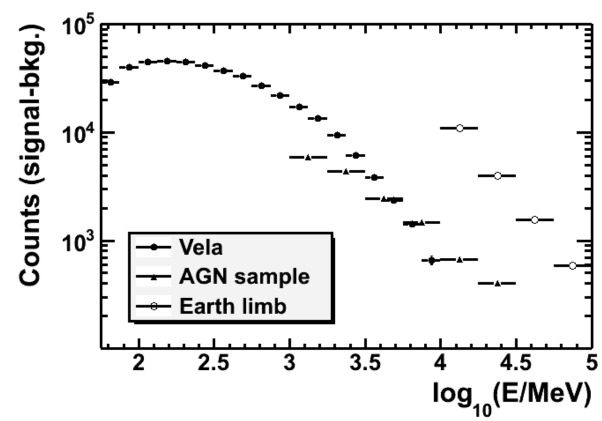




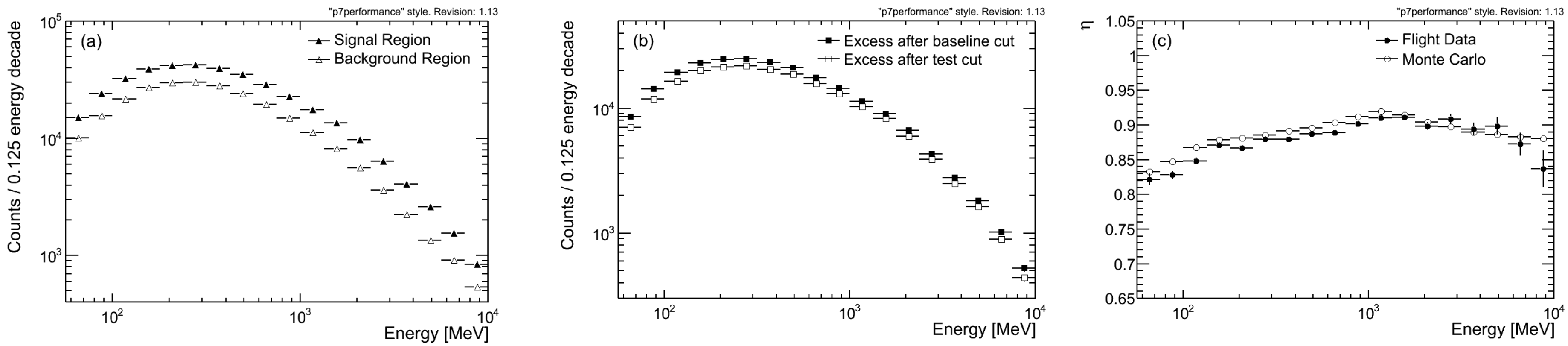
Show for P7TRANSIENT event class

Calibration Sample	Method
Vela pulsar (2 years) 15° ROI, $q_{z,vela} > 85°$ Very clean bkg. subtraction but cuts off around 3 GeV	Phase-gated
30 Bright, isolated AGN (2 years) 6° ROI, $q_z > 100°$, E > 1 GeV Need small PSF for bkg. subtraction	Aperture
Earth limb (200 limb-pointed orbits) E > 10 GeV Difficult to model earth limb emission below ~ 10 GeV.	Zenith Angle cut
All Sky E > 10 GeV (also prescaled samples at lower E) Useful for optimizing selections, but not precise	Latitude



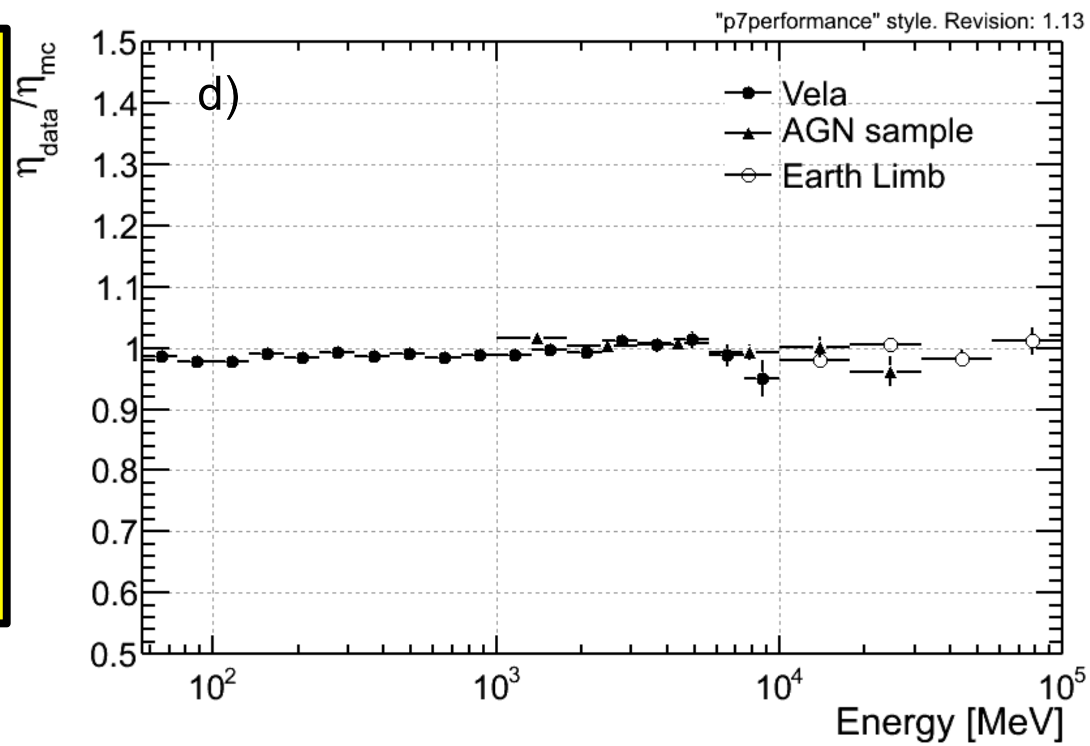


MC Efficiency Validation Technique

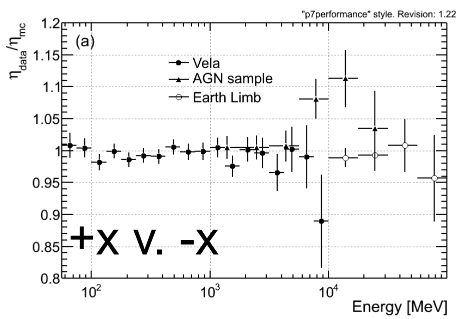


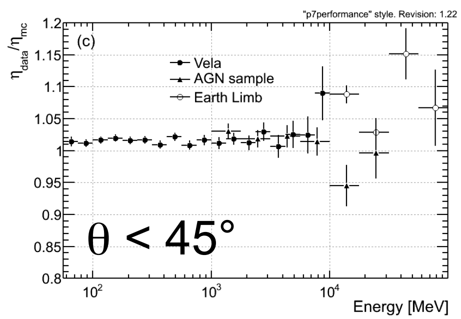
Method for data/MC efficiency comparison:

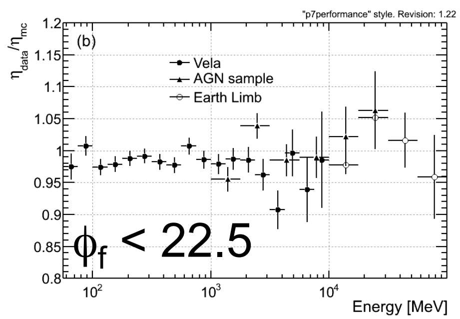
a) Counts spectra in signal and background regions
b) Excess in signal region before and after cut
c) Efficiency of cut on data and MC
d) Ratio of η_{data} / η_{mc}

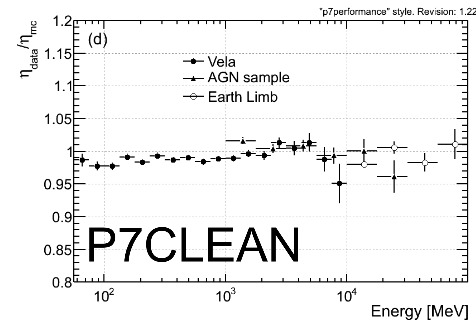


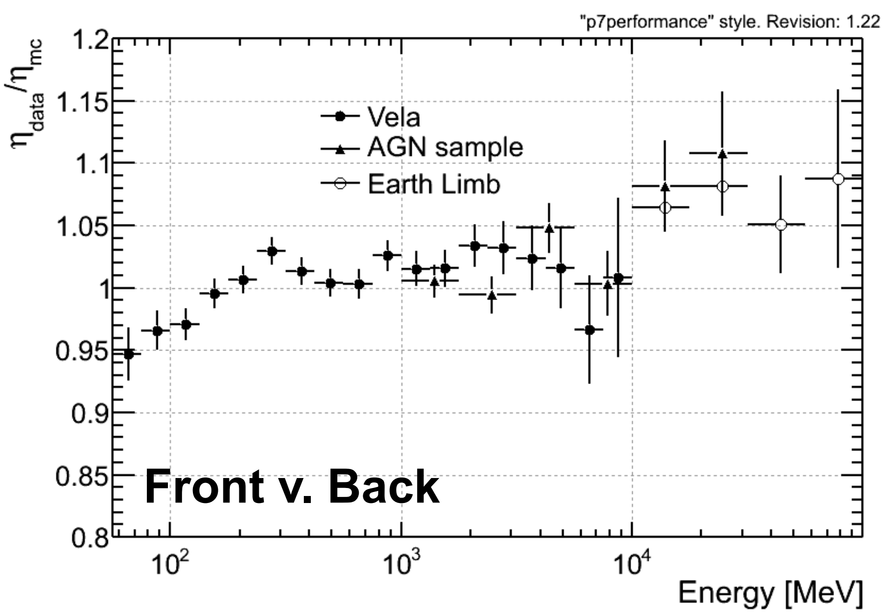
Consistency Checks and A_{eff} Error Bars

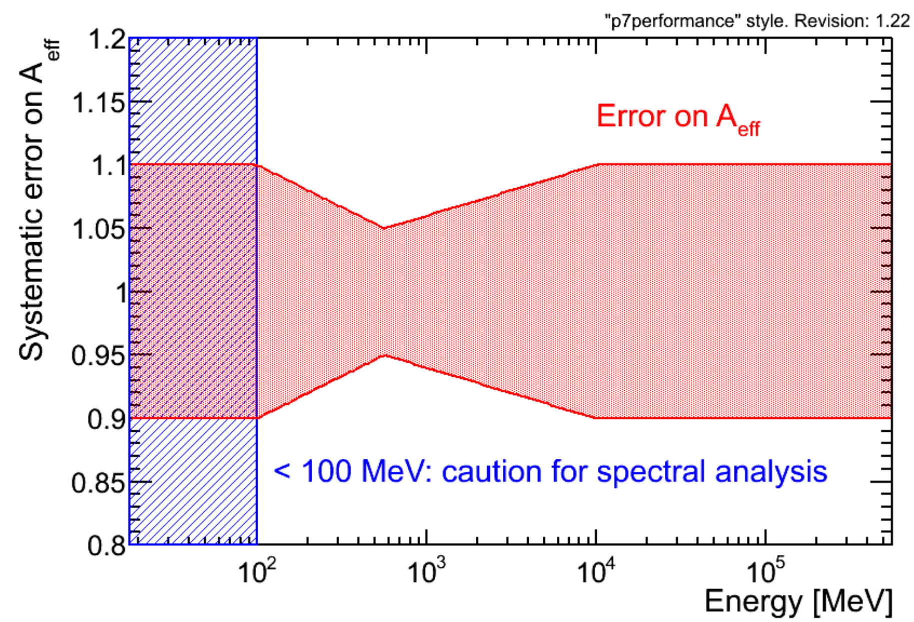










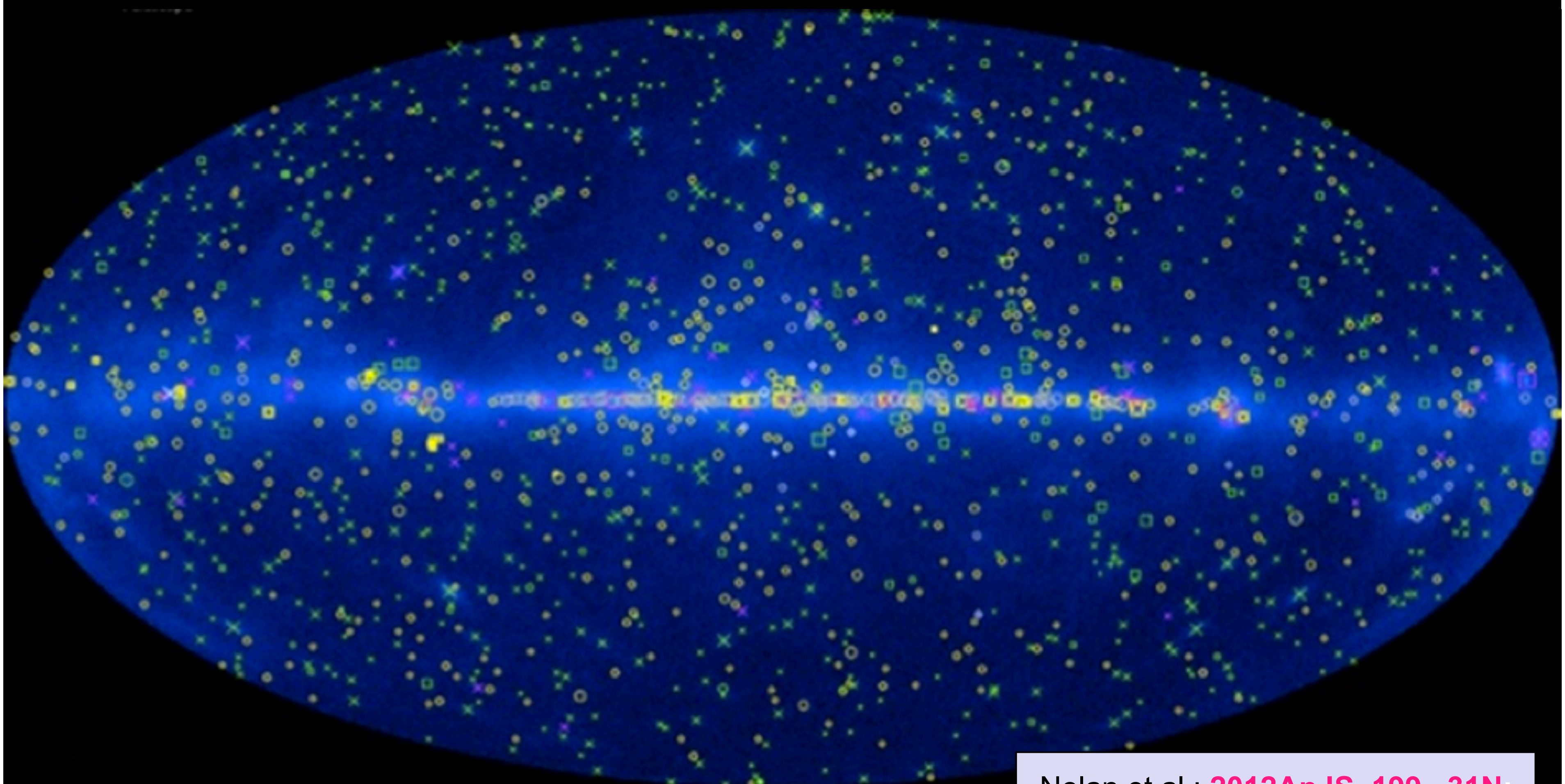


Most consistency checks yield excellent results

Front/Back fraction (bottom left) sets scale for A_{eff} errors (bottom right)

Recent Scientific Highlights

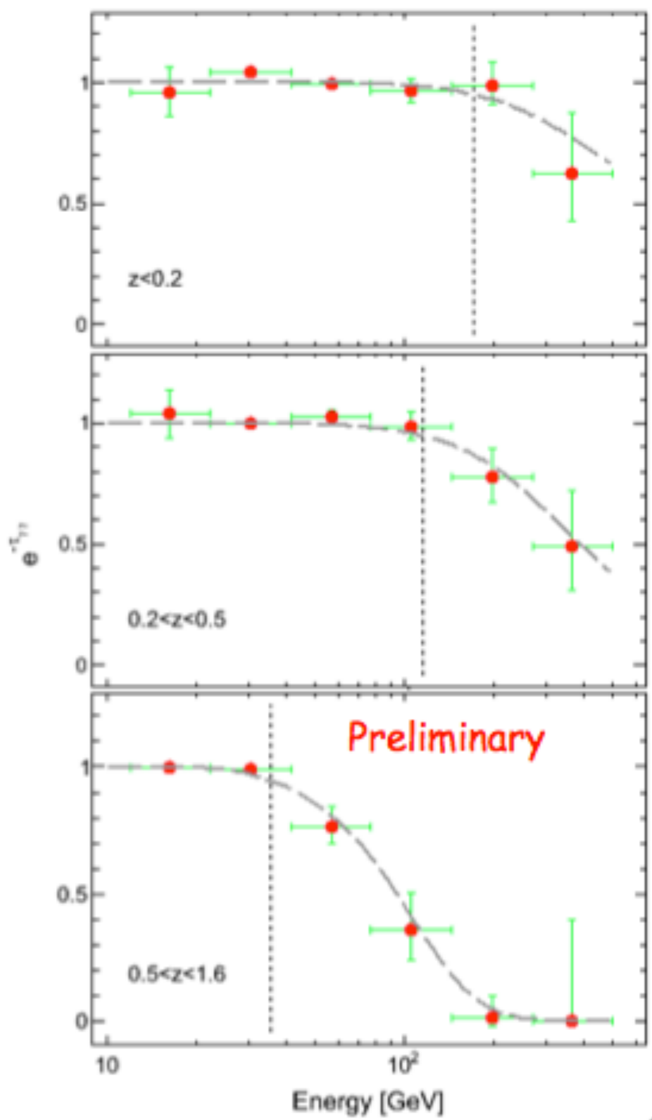
2FGL Catalog

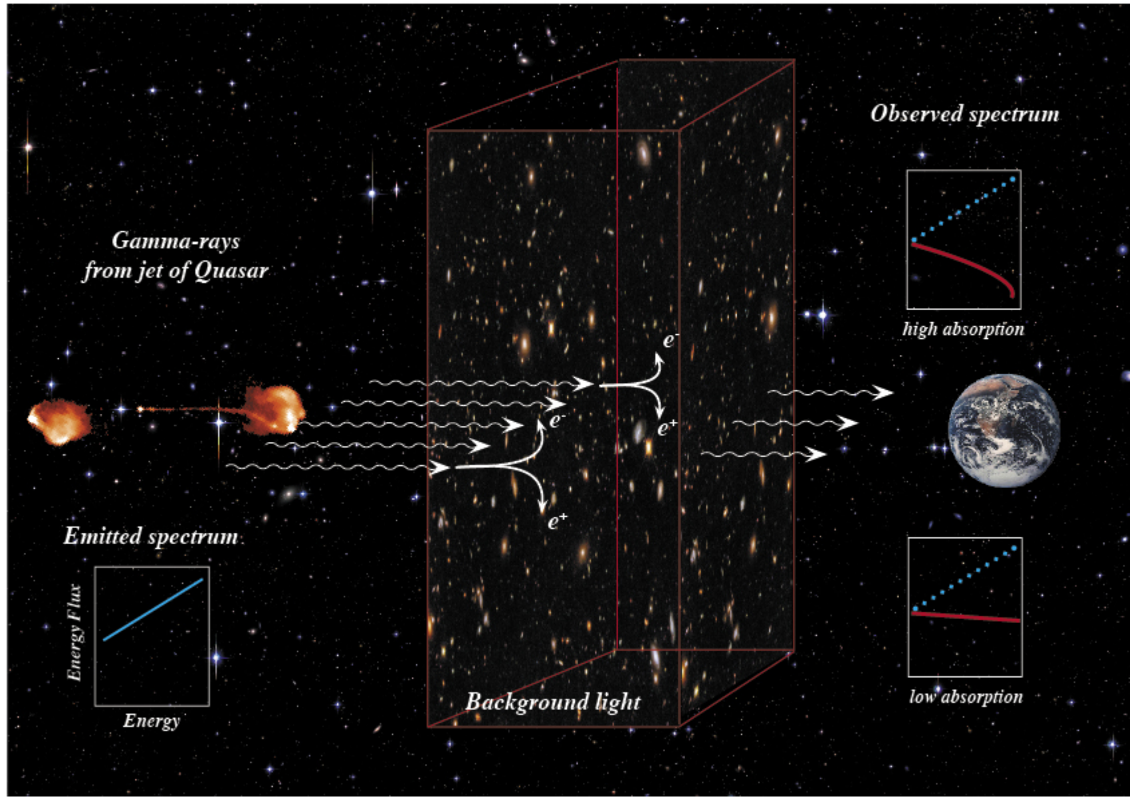


Nolan et al.: 2012ApJS..199...31N

1800+ γ-ray sources, >10 source classes: AGN, Pulsars, PWN, SNR...

Measuring the Extra-Galactic Background Light





Ackermann et al.: 2012Sci...338.1190A

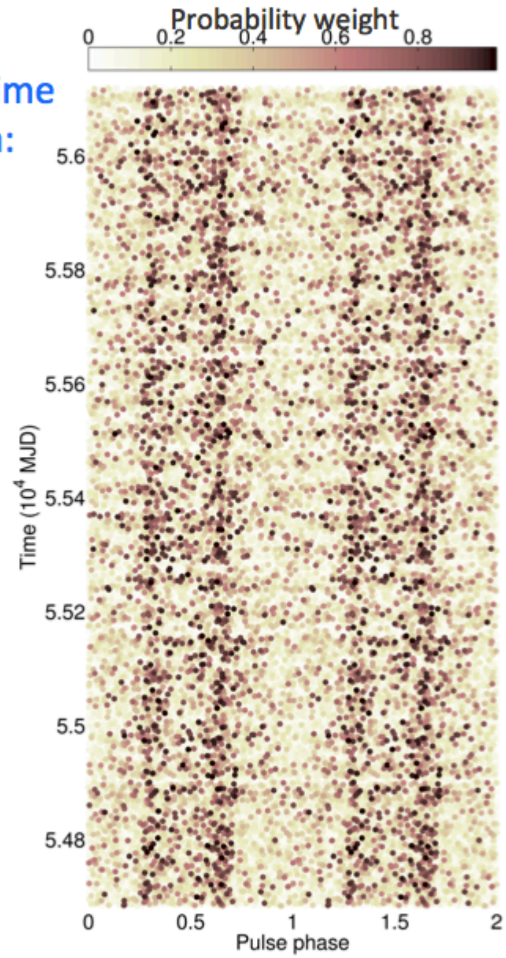
Redshift dependent high-energy spectral changes of Blazars used to quantify EBL

Millisecond Pulsar Blind Search Discovery

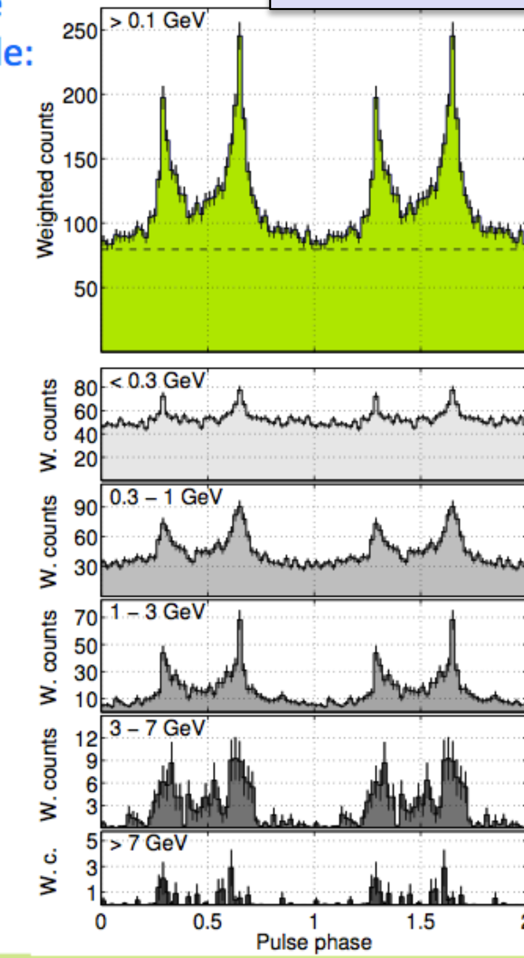
Pletsch et al.: 2012Sci...338.1314P

Fig.1.

Phase-time diagram:



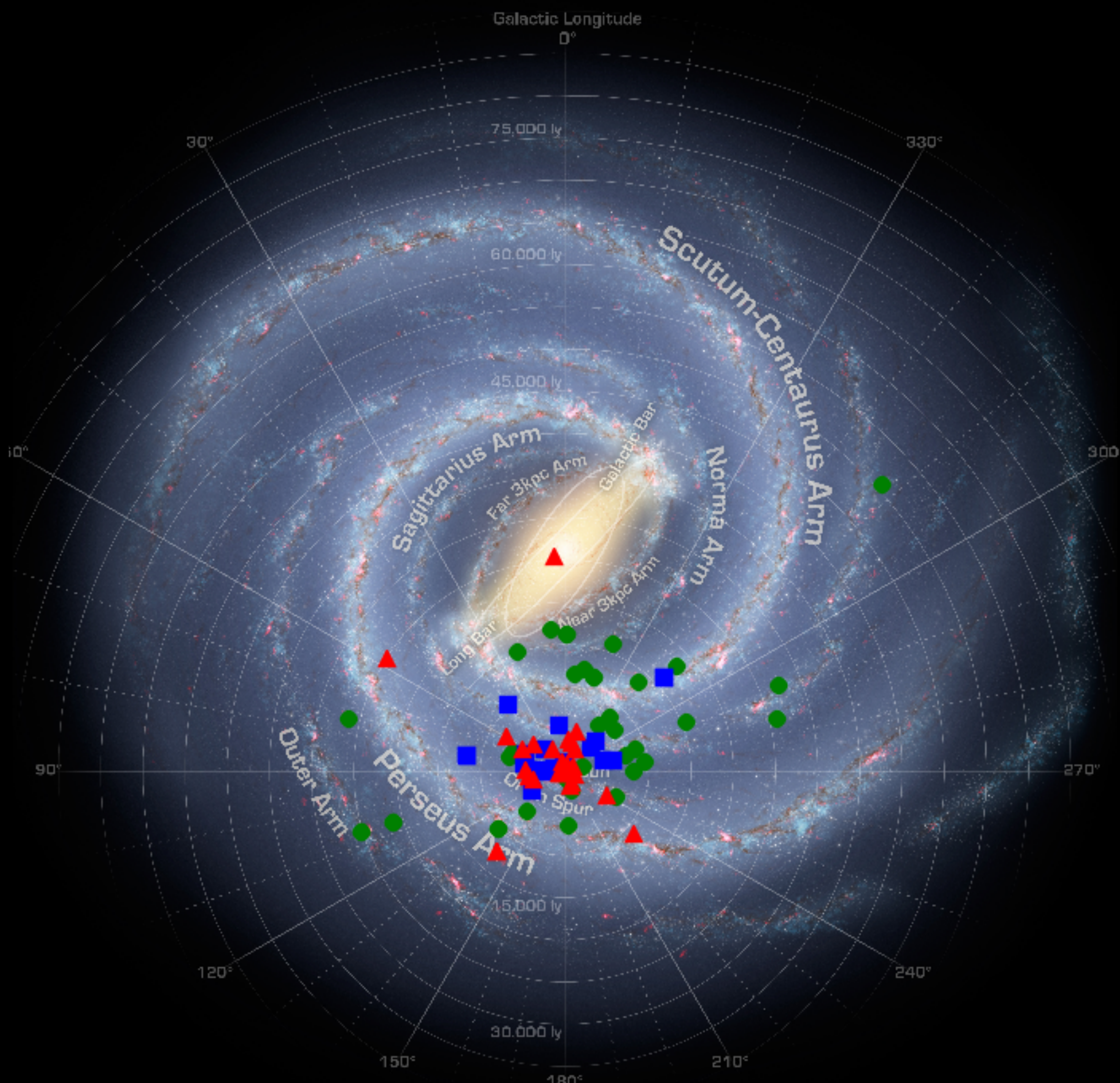
Pulse profile:



- Significant emission at all phases.
- Pulsations out to > 7 GeV.
- Found no orbital modulation of gamma-ray flux.

First discovery of MSP in a blind search in gamma rays
Use optical data to estimate orbital parameters to seed search

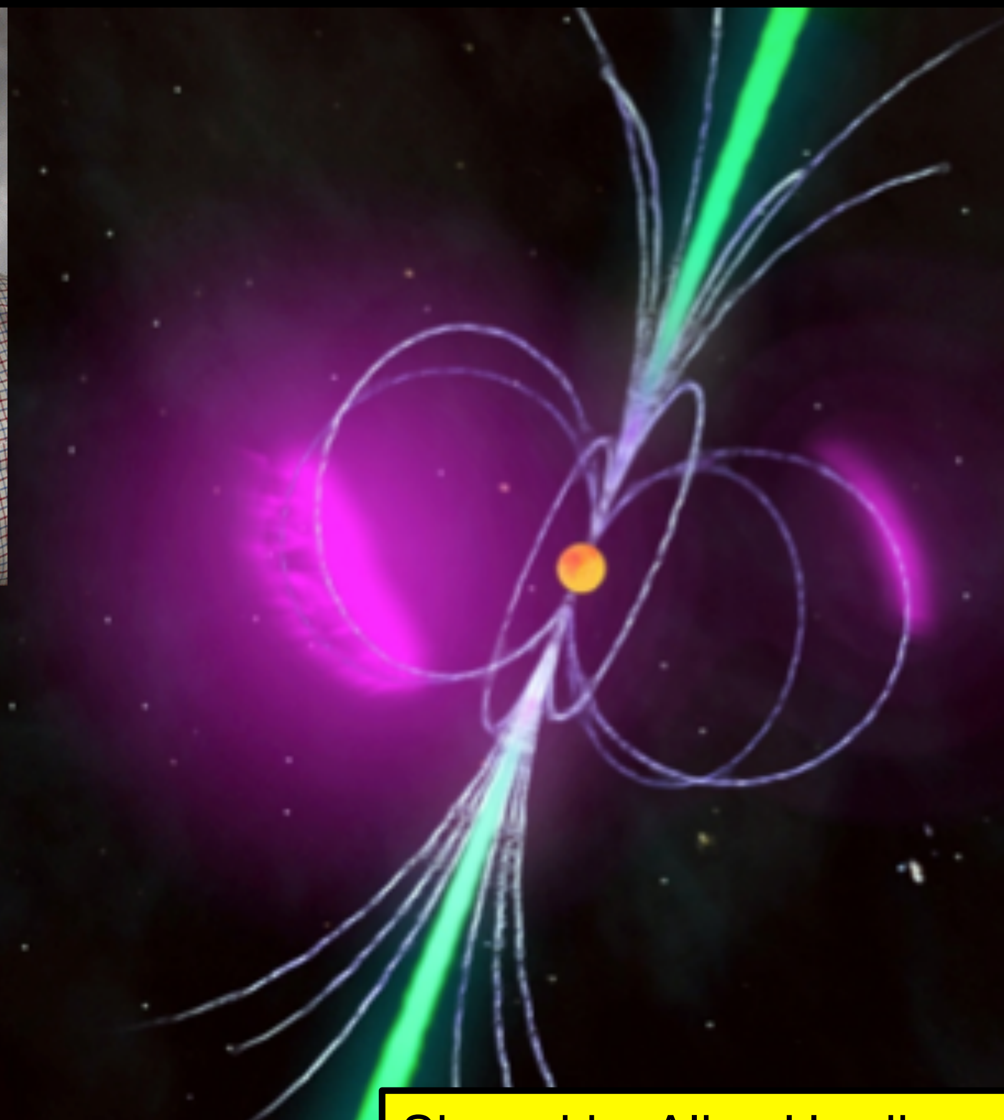
Second LAT Pulsar Catalog

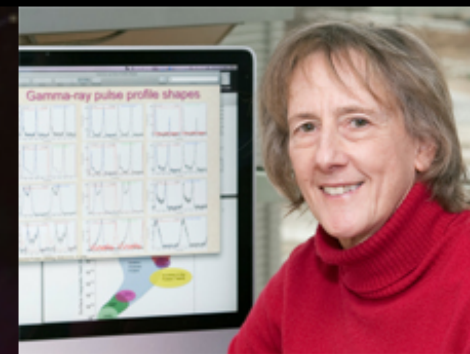


- 117 Pulsars in LAT 2PC
- Constellation of MSP can allow for extremely long baseline gravitational wave detection

To be submitted to ApJS

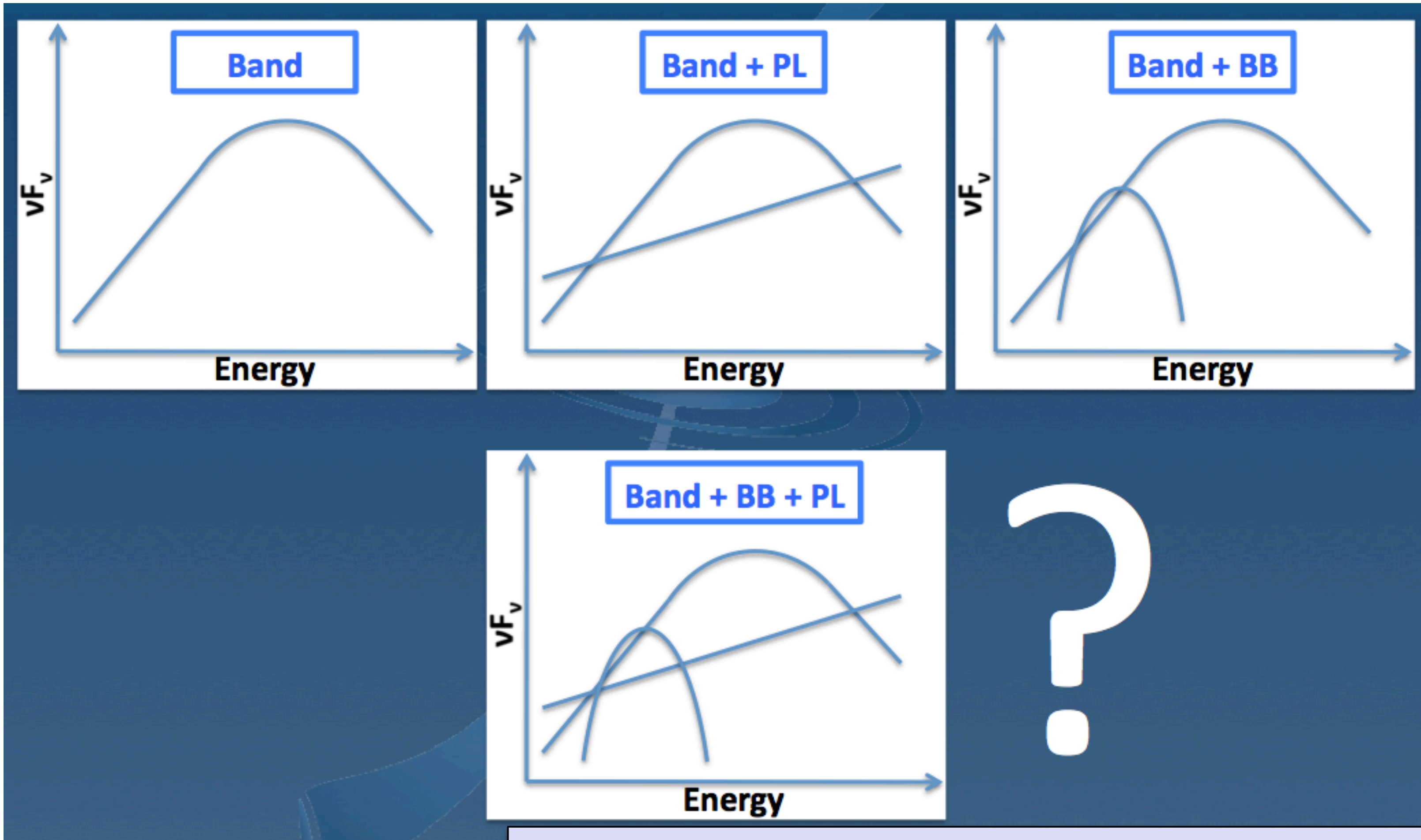
2013 Rossi Prize Awarded for Pulsar Modeling





Shared by Alice Harding and Roger Romani

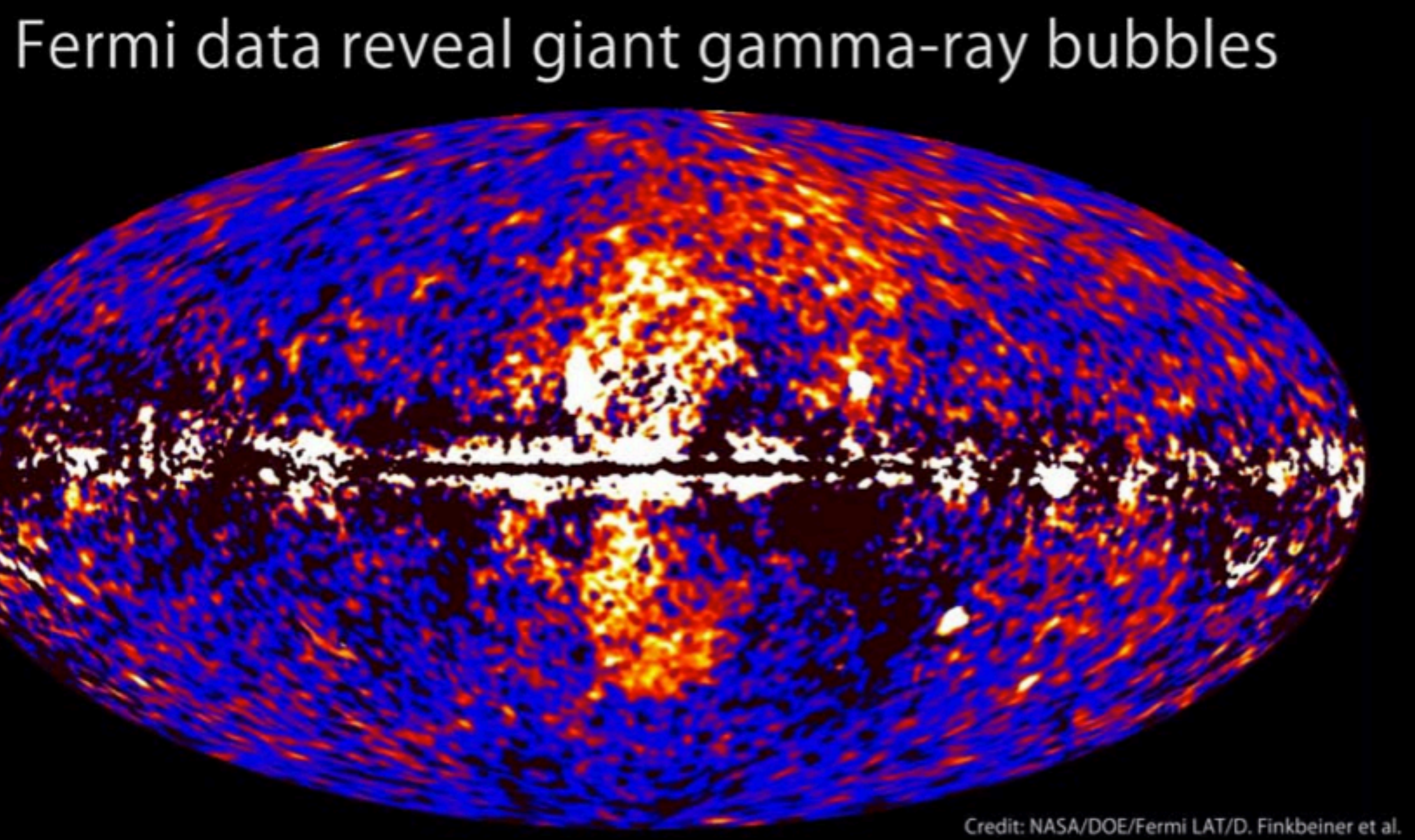
Science Highlights: GRB Components



Fermi-LAT GRB Catalog **Submitted to ApJS:** 2013arXiv1303.2908F

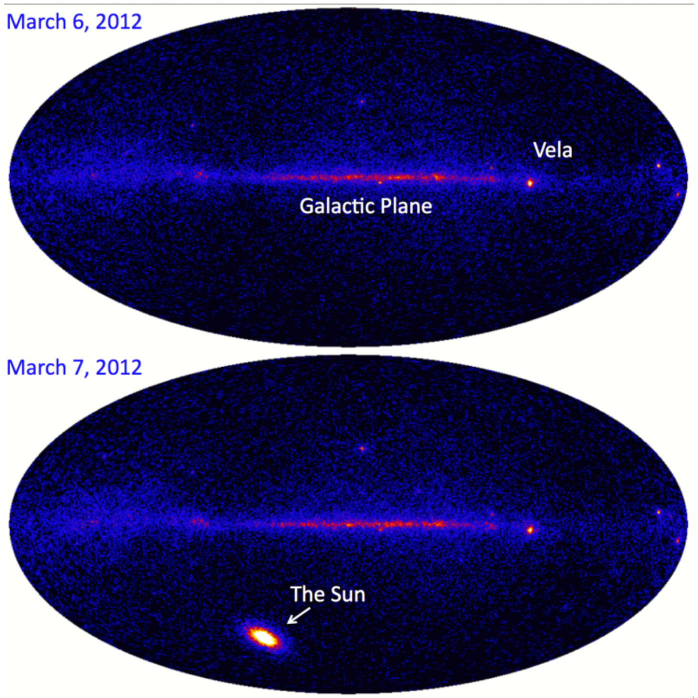
Performing time-resolved spectroscopy of GRBs, allowing us to track the evolution of various component during the burst

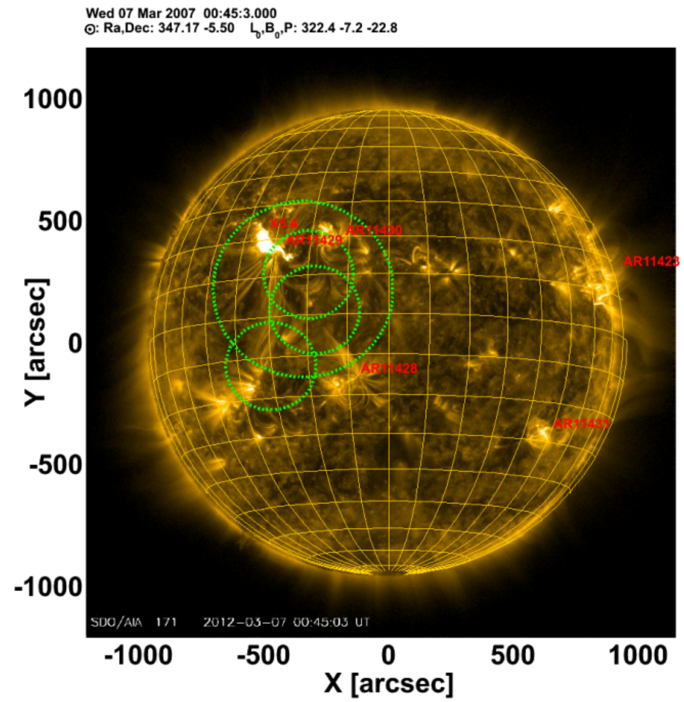
Fermi Lobes: Unexpected Diffuse Emission



Su, Slatyer & Finkbiener: arXiv:1005.5480
Hooper & Slayter arXiv:1302.6589

The Active Sun



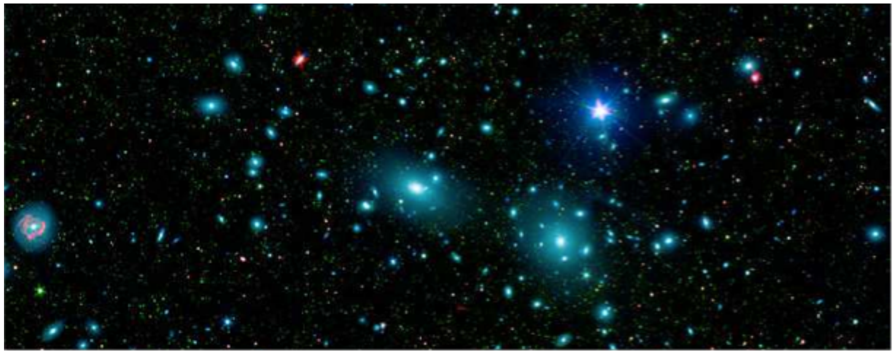


- A very bright Solar Flare:
- Brighter than the rest of the g-ray sky
  - 1000 times the flux of the steady Sun; 100 times the flux of Vela; 50 times the Crab flare;
- High energy emission (>100 MeV, up to 4 GeV)
- Lasts for ~20 hours
- From same Active Region as at other wavelengths

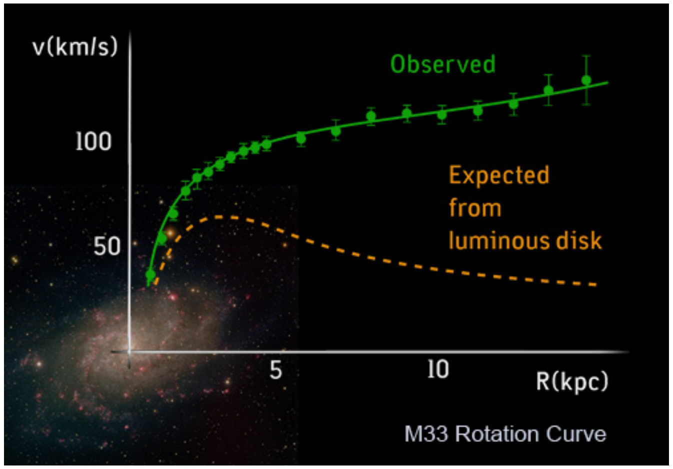
To be Submitted to ApJ. Also a paper on flares from March / June 211

INDIRECT SEARCHES FOR DARK MATTER

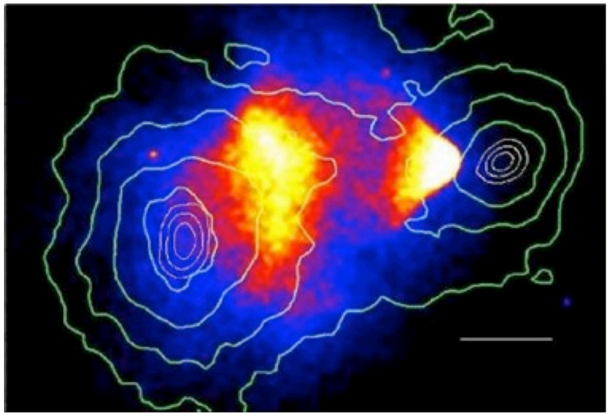
Evidence for / Salient Features of Dark Matter



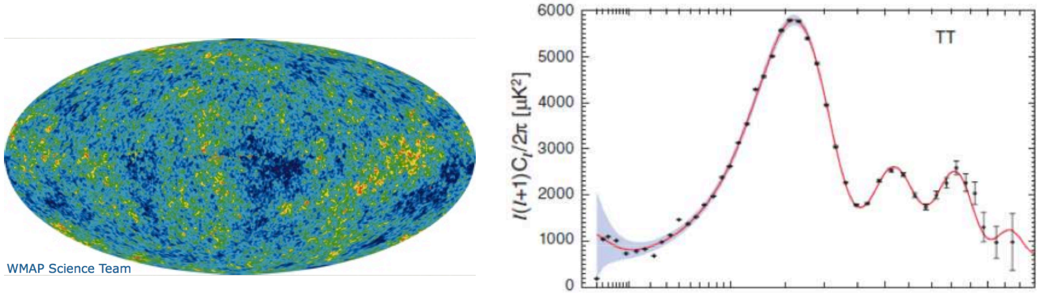
*Comprises **majority** of **mass** in Galaxies*
Missing mass on Galaxy Cluster scale
Zwicky (1937)



*Large **halos** around Galaxies*
Rotation Curves
Rubin+(1980)

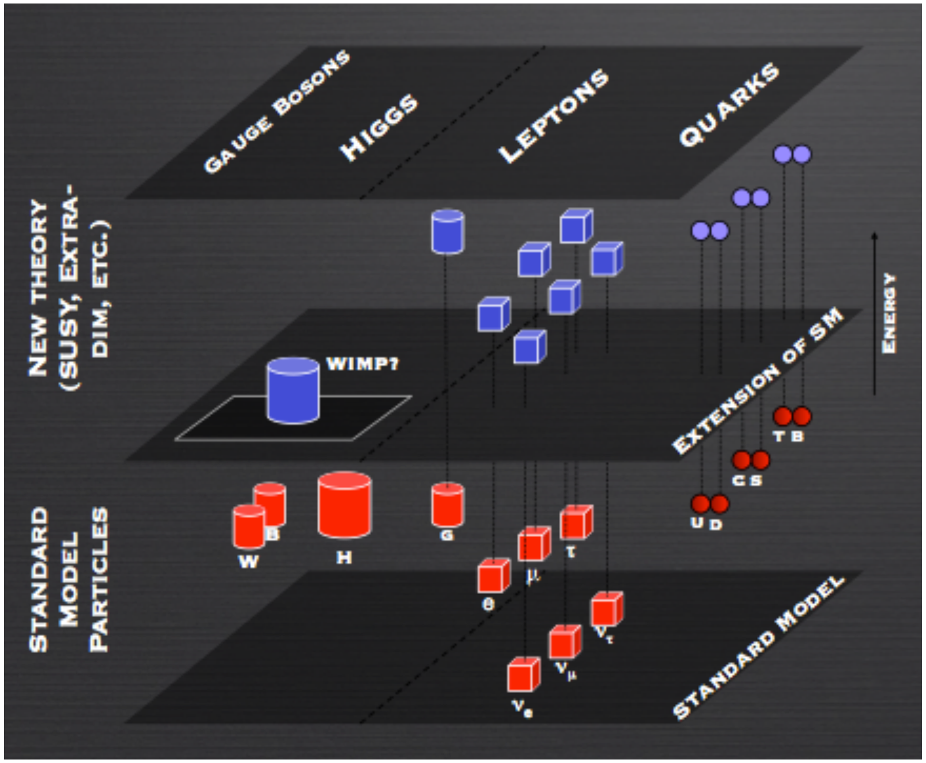


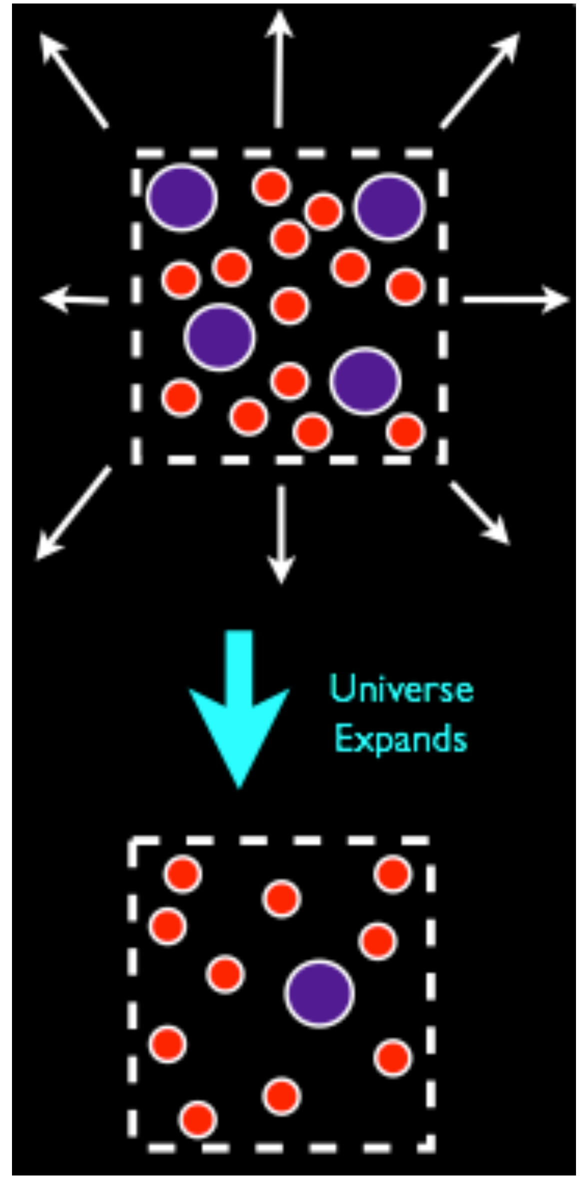
*Almost **collisionless***
Bullet Cluster
Clowe+(2006)



Non-Baryonic
CMB Acoustic Oscillations
WMAP(2010)

Particle Physics offers Dark Matter Candidates

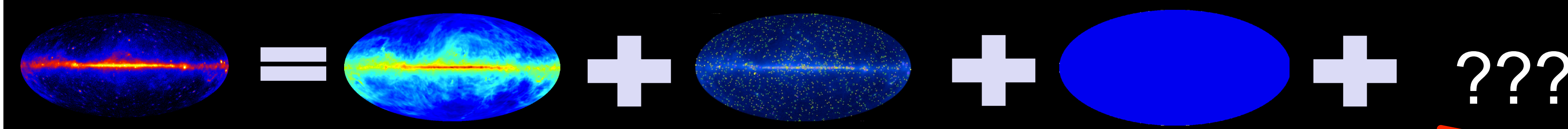


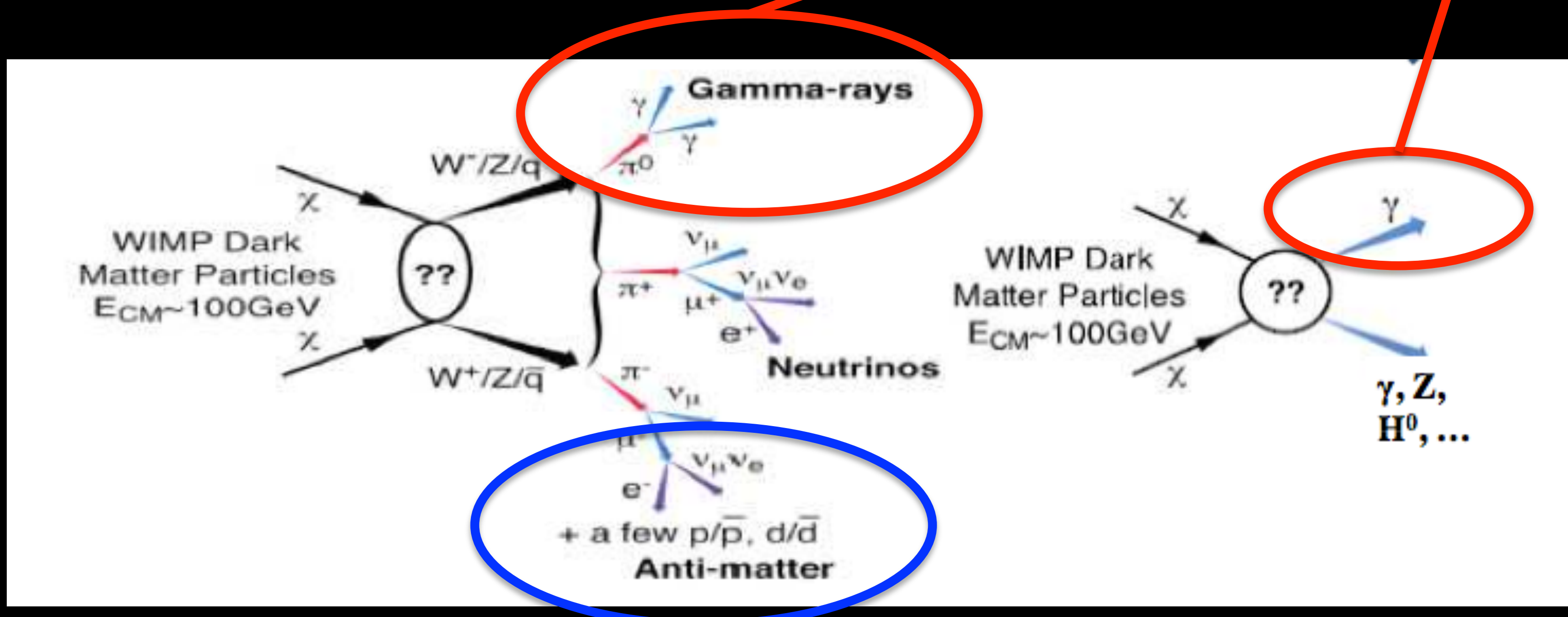


- Weakly Interacting Massive Particles (WIMPs) are an interesting DM candidate

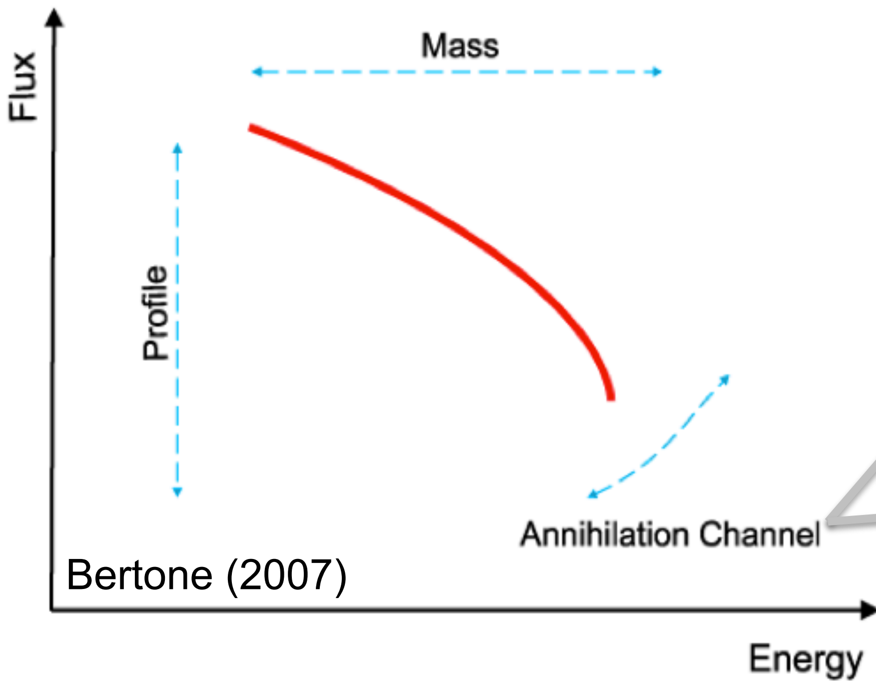
- "WIMP Miracle", WIMPs as thermal relic:
Mass scale ~ 100 GeV
$<\sigma v> \sim 3\ 10^{-26}\ cm^3\ s^{-1}$

Indirect Searches for DM in the GeV Sky

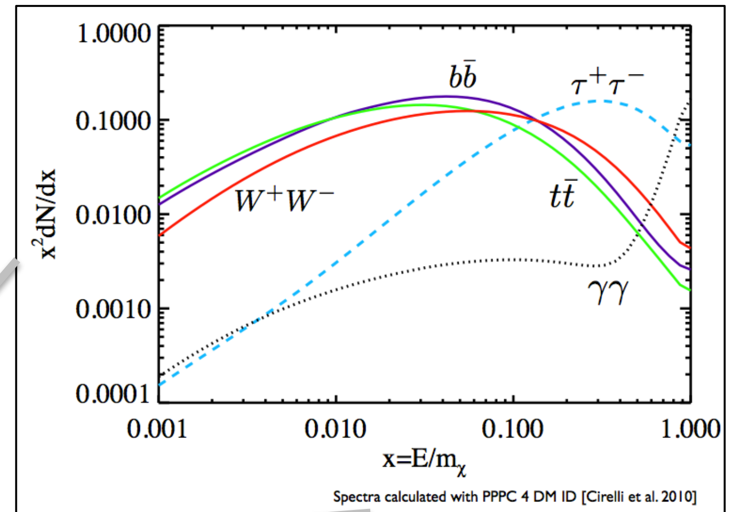




Dark Matter Signatures in γ-ray Sky



Bertone 2007



Particle Physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi} \frac{< \sigma_{ann} v >}{2 m^2_{WIMP}} \sum_f \frac{dN^f_\gamma}{dE_\gamma} B_f$$

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

Astrophysics (J-Factor)

DARK MATTER SEARCH STRATEGIES AND RESULTS

Dark Matter Search Strategies

Satellites

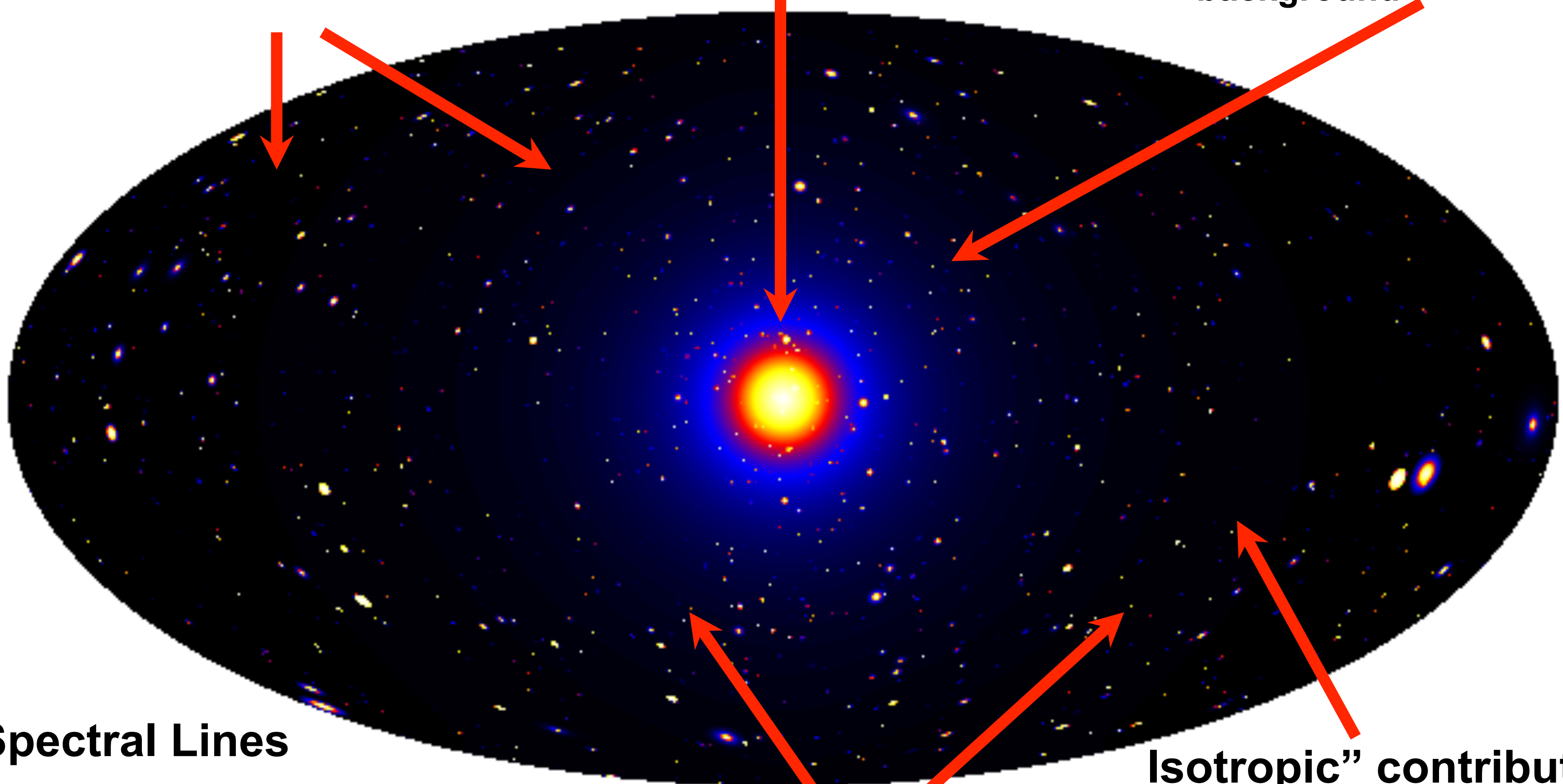
Low background and good source id, but low statistics

Galactic Center

Good Statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



Spectral Lines

Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

Galaxy Clusters

Low background, but low statistics

Isotropic" contributions

Large statistics, but astrophysics, galactic diffuse background

Dark Matter simulation:
Pieri+(2009) arXiv:0908.0195

Search Strategies (against the g-ray Sky)

Satellites

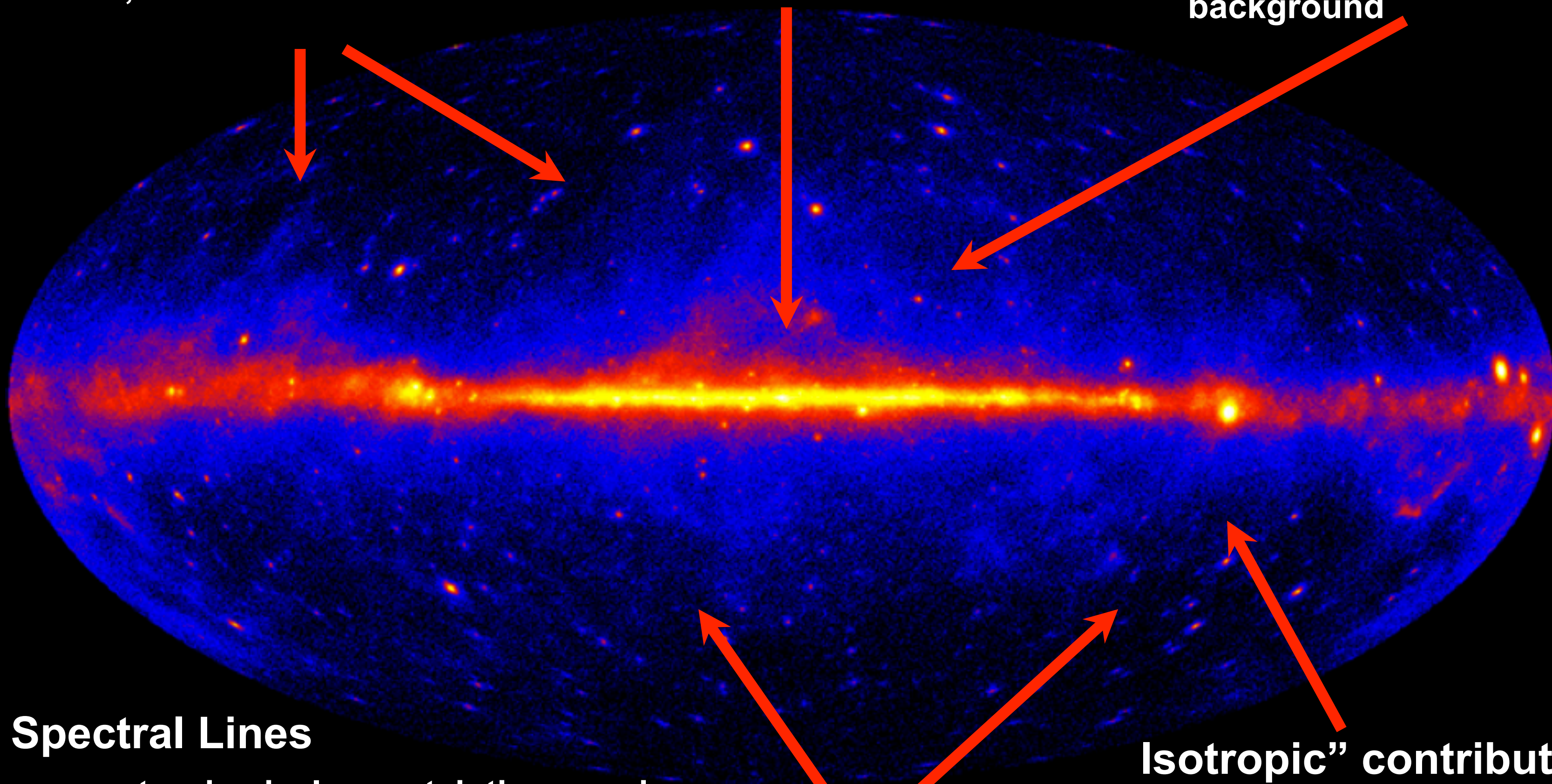
Low background and good source id, but low statistics

Galactic Center

Good Statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



Spectral Lines

Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

Galaxy Clusters

Low background, but low statistics

Isotropic" contributions

Large statistics, but astrophysics, galactic diffuse background

3 Years Sky > 1 GeV

Limits on $\langle\sigma v\rangle$ at 10GeV ($cm^3 s^{-1}$)

Satellites

dSph ~ 2×10^{-26}

UNID ~ 2×10^{-24}

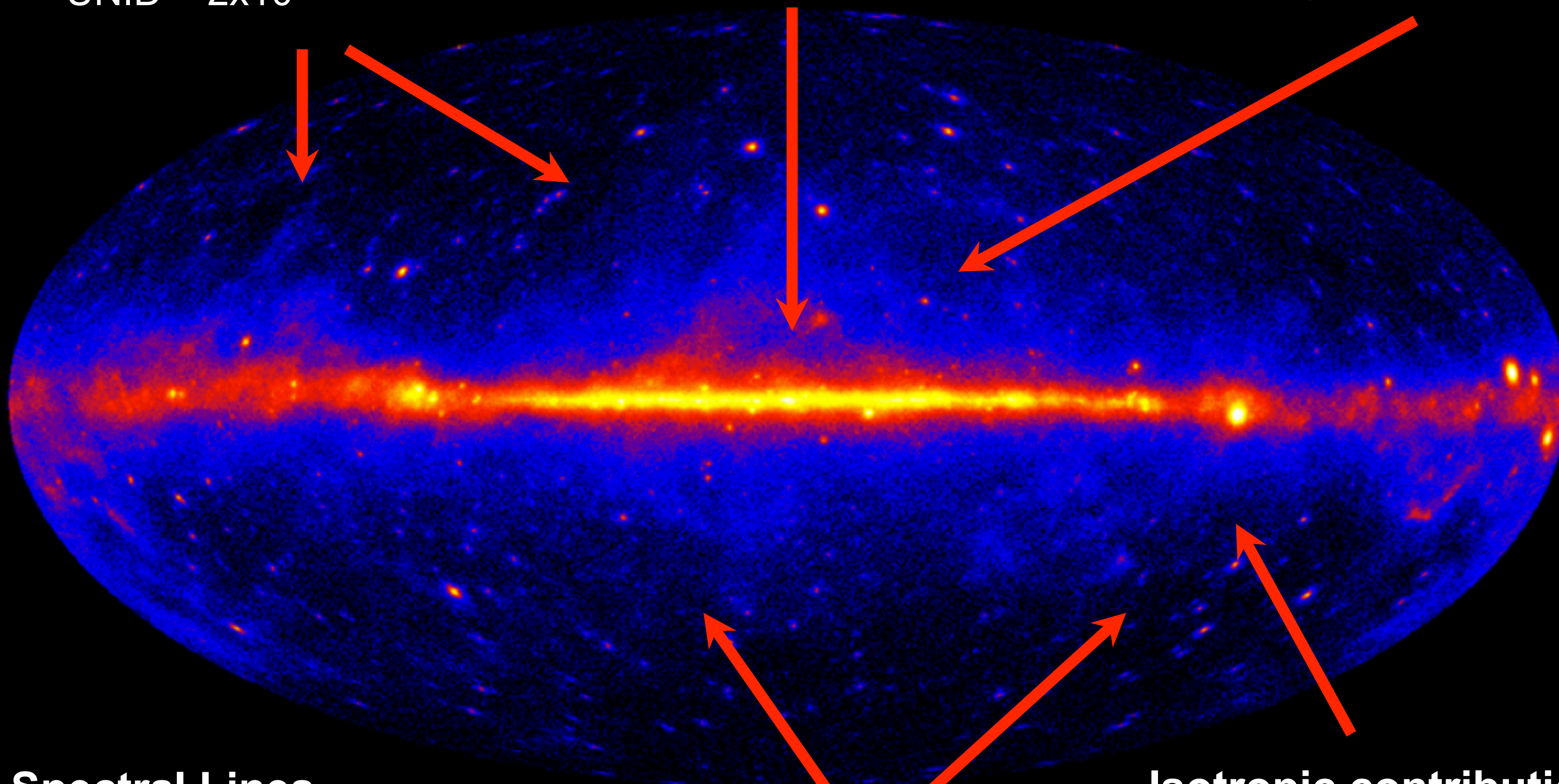
Galactic Center

Vary w/ model & method

Milky Way Halo

W/ bkg. model: 2×10^{-26}

No bkg. model: 2×10^{-25}



Spectral Lines

100 GeV ~ 8×10^{-27}

Galaxy Clusters

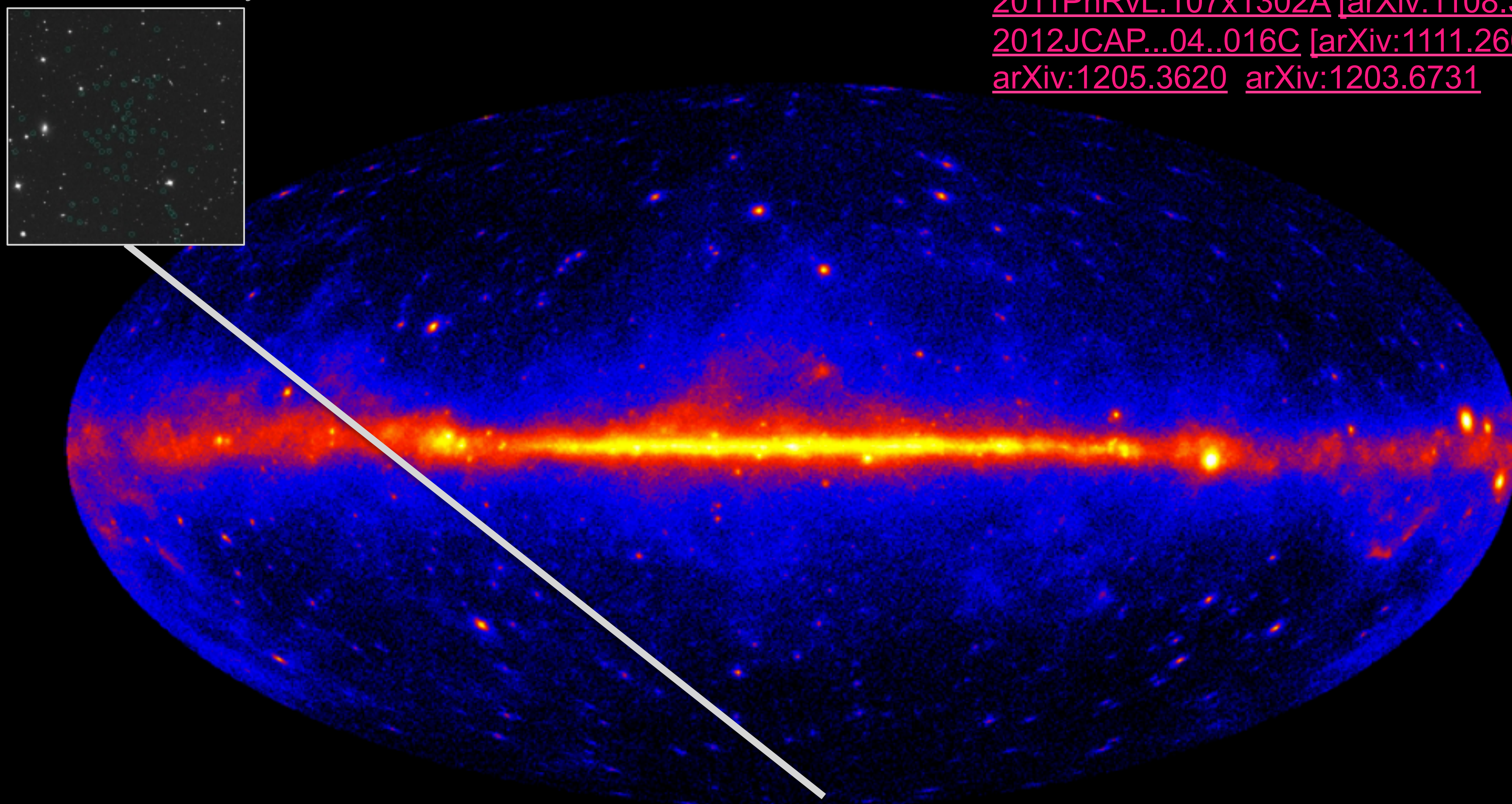
~5×10^{-25}

Isotropic contributions

Vary w/ model & method

Searches for DM in Dwarf Spheroidal Galaxies

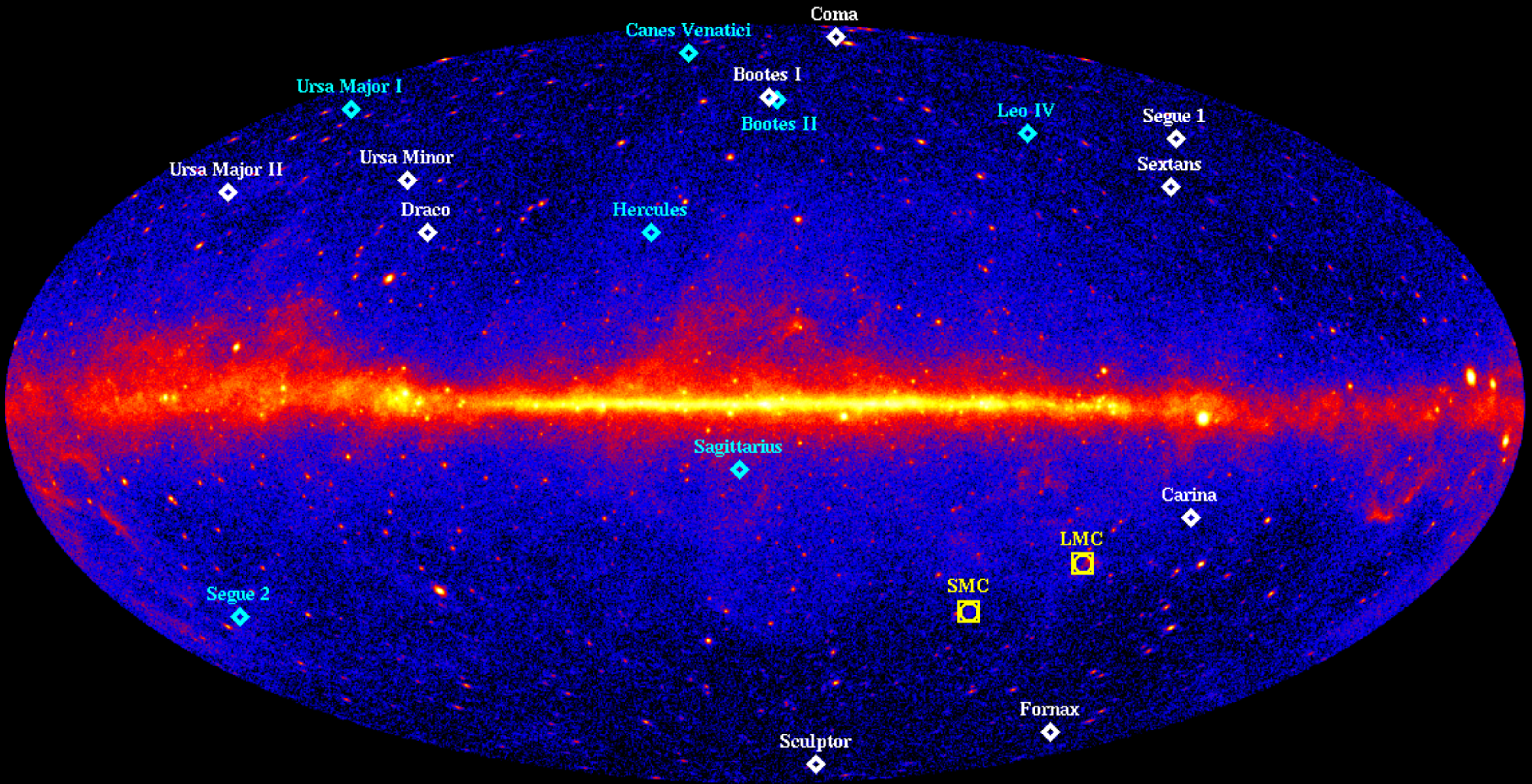
Segue 1
Keck Observatory



2010ApJ...712..147A [arXiv:1001.4531]
2011PhRvL.107x1302A [arXiv:1108.3546]
2012JCAP...04..016C [arXiv:1111.2604]
arXiv:1205.3620 arXiv:1203.6731

- Look for γ-ray emission from Dwarf Spheroidal galaxies with large, well measured, J-factors at high Galactic latitudes
- This is as a low-signal, low-background search strategy

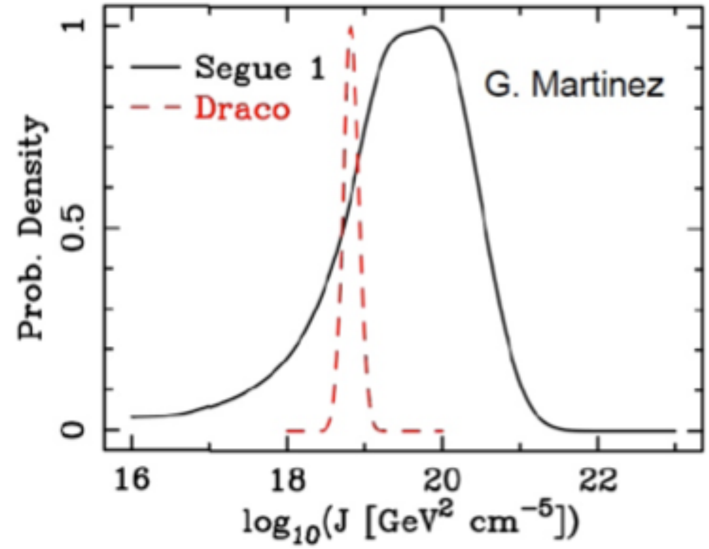
DM in dSph: Search Targets



- Roughly two dozen Dwarf Spheroidal satellite galaxies of the Milky Way
- Some of the most dark matter dominated objects in the Universe
- Negligible astrophysical γ-ray production expected

DM in dSph: Search Strategy

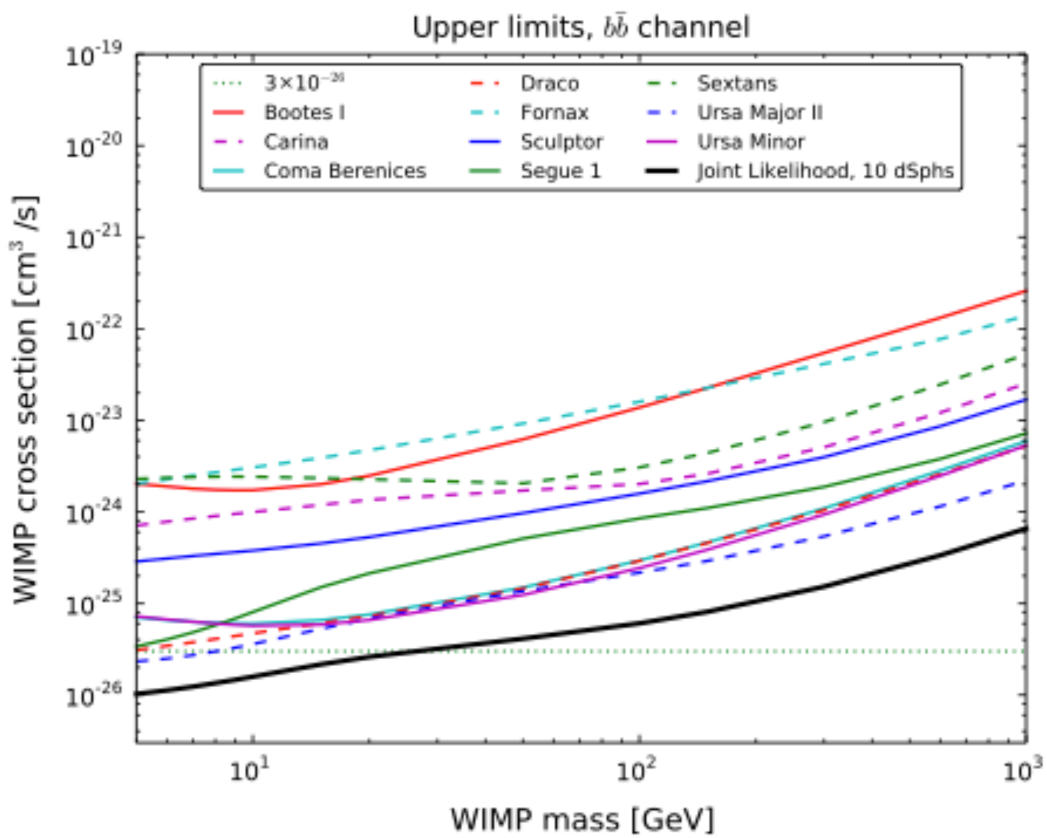
- Data Analysis:
  - Combined Likelihood analysis of 10 dSph
    - 2 years of data (P6_V3_DIFFUSE)
      - Standard data selection (quality & θ_z cut)
    - 200 MeV - 100 GeV
    - 4 annihilation channels
  - Include statistical uncertainties in J-factors in likelihood formalism
    - They can be large, and vary between dSph
  - Joint Likelihood:



$$L(D\,|\,\underbrace{\mathbf{p_m}}_{\text{Shared by all dwarfs}},\underbrace{\{\mathbf{p_k}\}}_{\text{Fit for each dwarf}}) = \prod_k L_k^{\mathrm{LAT}}(D_k\,|\,\mathbf{p_m},\mathbf{p_k}) \times \underbrace{\frac{1}{\ln(10)\,J_k\sqrt{2\pi}\,\sigma_k}\,e^{-(\log_{10}(J_k)-\overline{\log_{10}(J_k)})^2/2\sigma_k^2}}_{\text{Uncertainty in J-factor}}$$

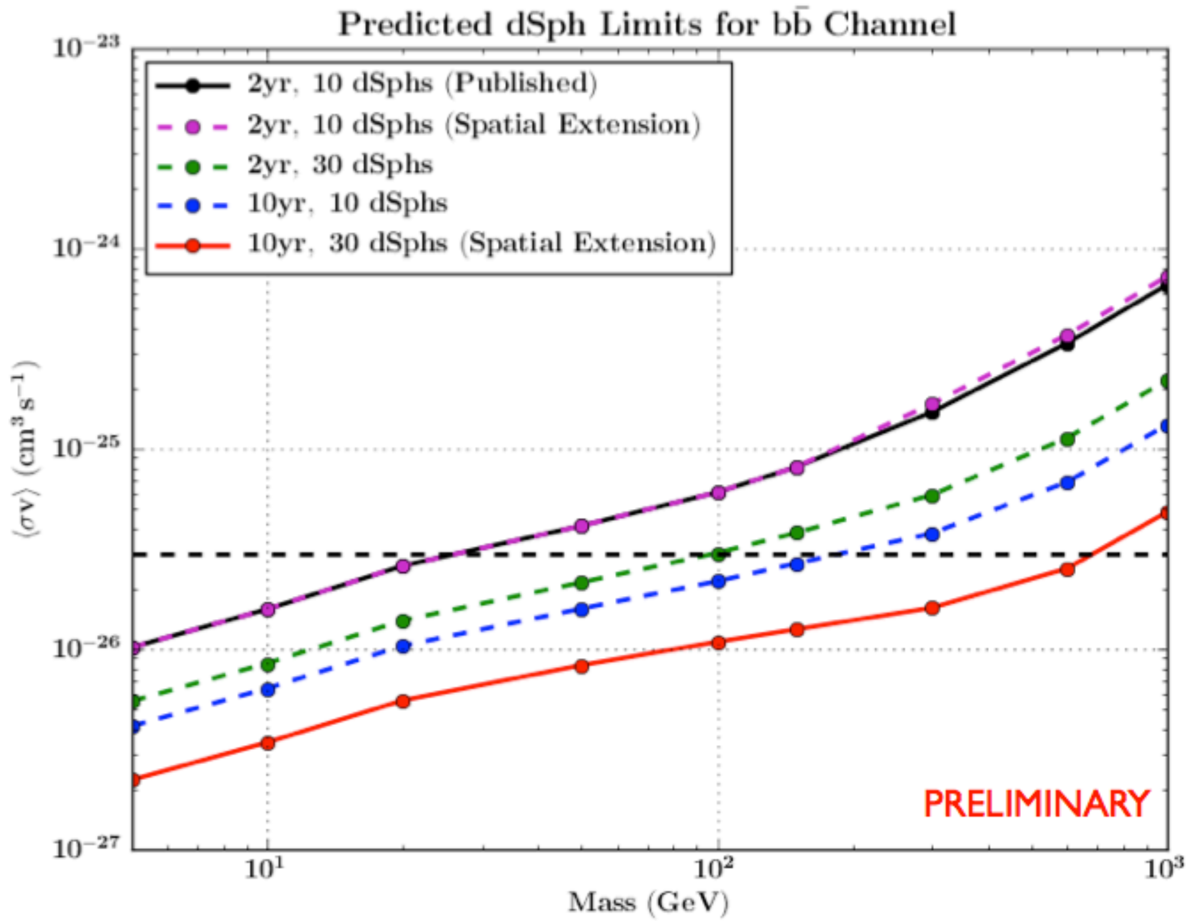
Ackermann et al.: 2011PhRvL.107x1302A

DM in dSph: Results



Combined upper limit excludes "canonical" thermal relic cross-section for annihilation into bb or $\tau^+\tau^-$ for masses below ~ 30GeV

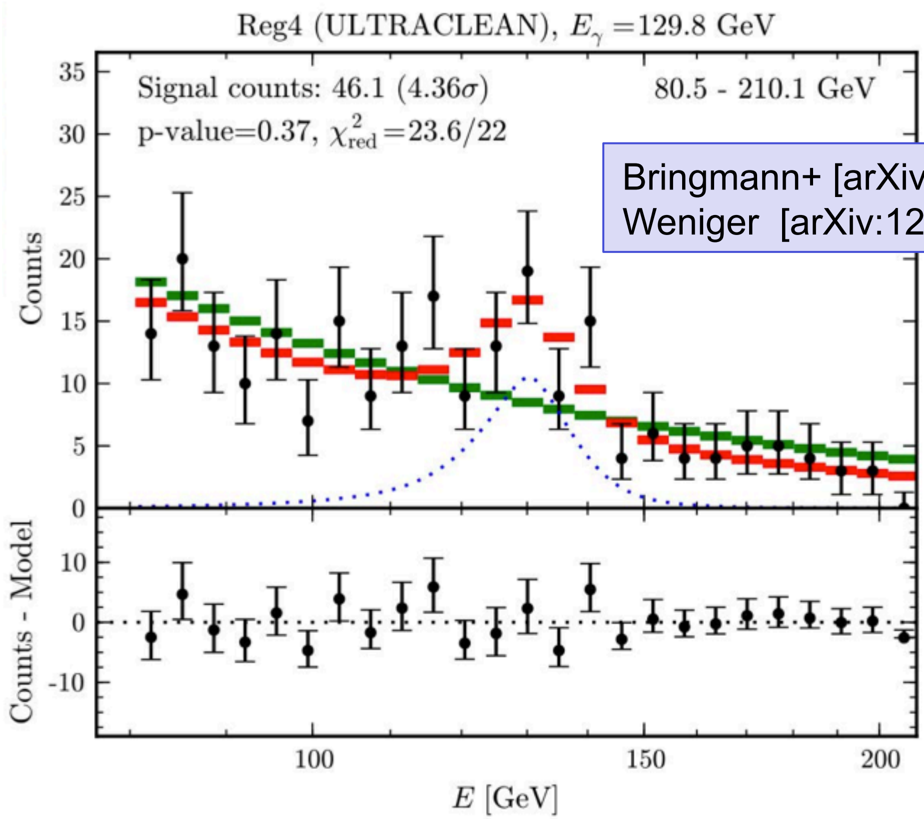
DM in dSph: Prospects



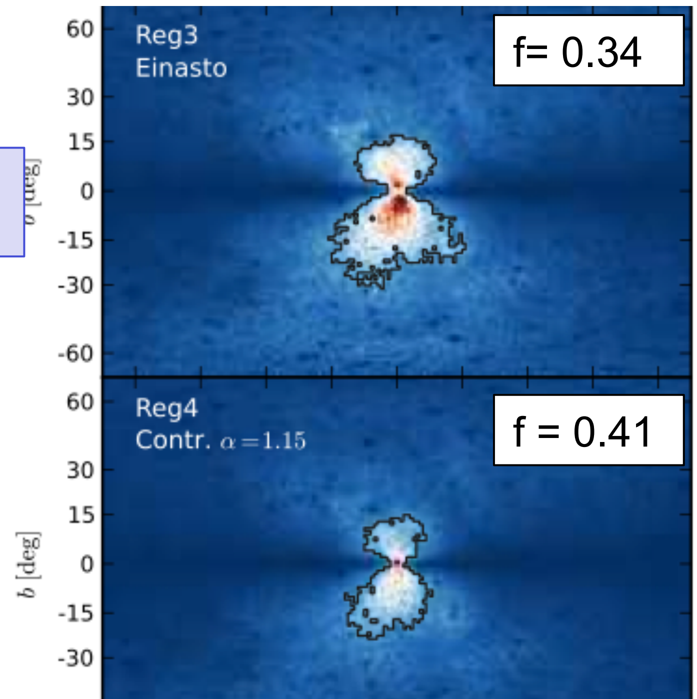
Discovery of new dSph and increased observing time should allow us to explore the thermal relic cross section up to almost 1TeV by the end of the mission

EVIDENCE FOR 130GeV γ-RAY LINE?

The Context: Narrow Feature at 130 GeV



Bringmann+ [arXiv:1203.1312]
Weniger [arXiv:1203.2797]



Fractional Residual (i.e., S/N):
$f = s_{local}^2 / n_s$

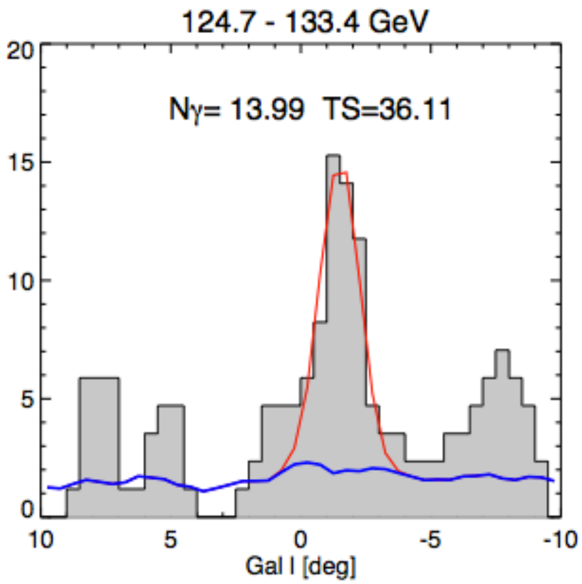
Bringmann et al. and Weniger showed evidence for a narrow spectral feature near 130 GeV near the Galactic center (GC).

•Signal is particularly strong in 2 out of 5 test regions, shown above.

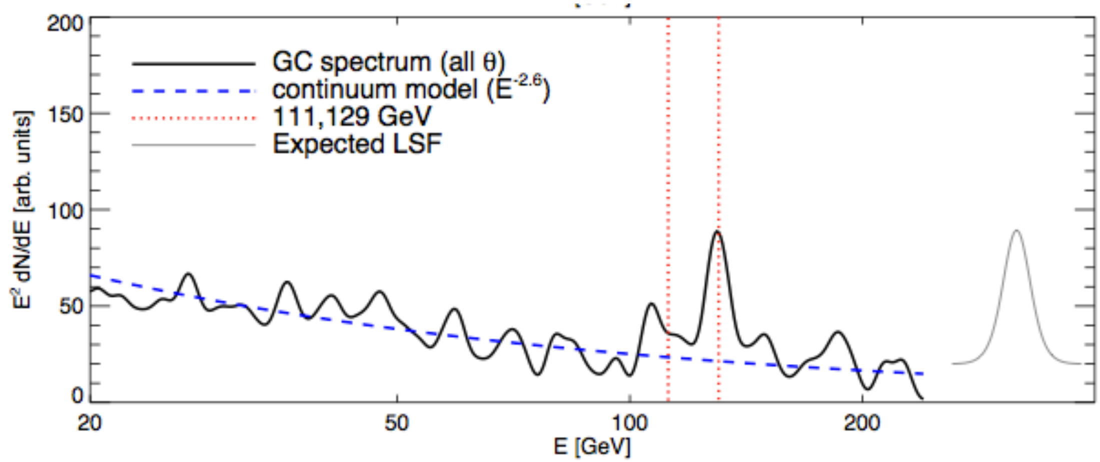
•Over 4σ, with S/N > 30%, up to ~60% in optimized regions of interest (ROI).

More Context

Gal. Long. Profile at ~130GeV



Energy Spectrum from GC



Su & Finbkbeiner [arXiv:1206.1616]

Su & Finkbeiner [arXiv:1206.1616v2] showed that the spectral feature was close to, but slightly offset from, the GC.

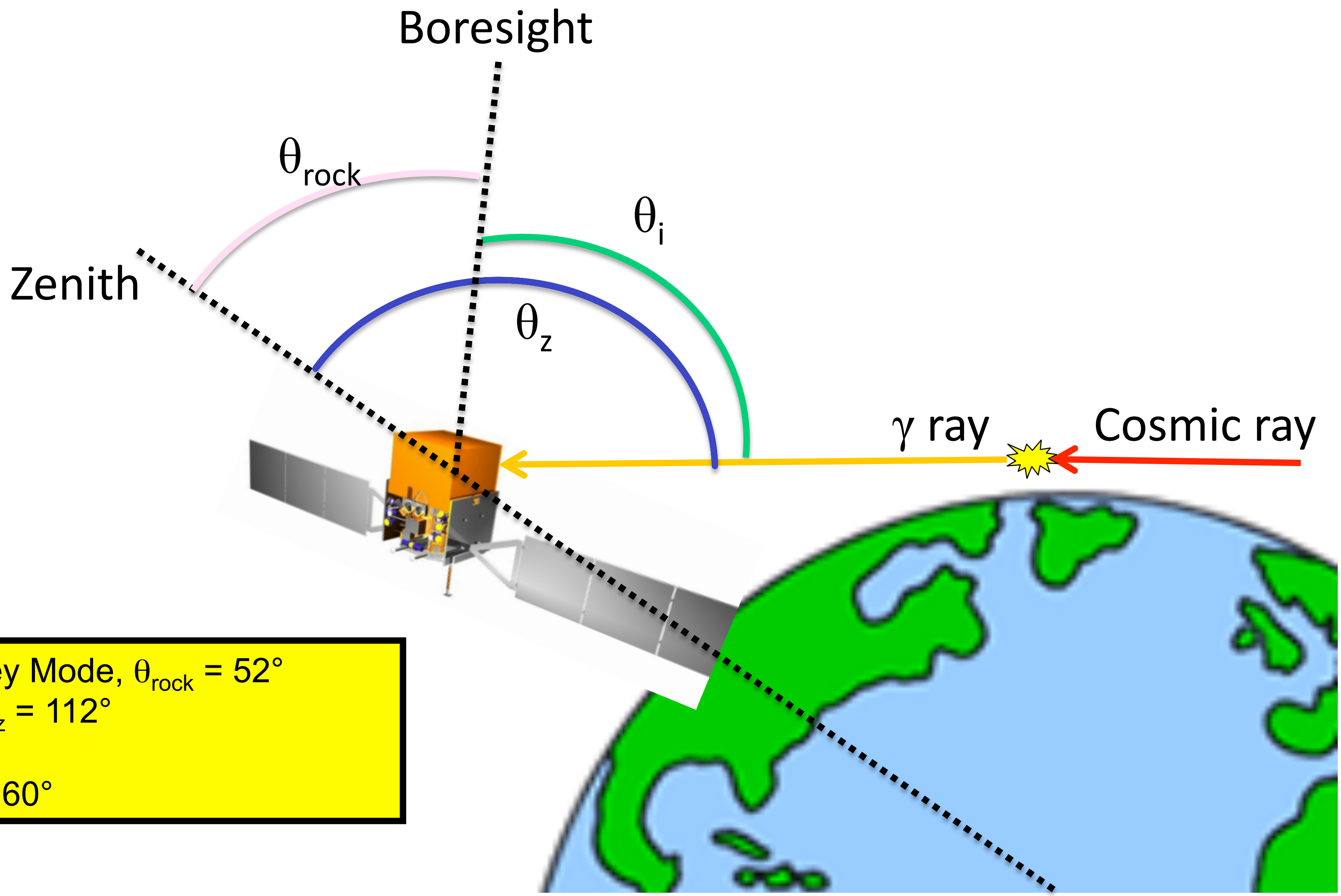
•Their likelihood analysis included the spatial morphology of signal, and a data-driven model of Galactic astrophysical backgrounds.

•They claimed **6.0σ** statistical significance, after a trials factor of ~6000, but acknowledge uncertainties of modeling the Galactic astrophysical backgrounds.

FERMI-LAT LINE SEARCH

Methodology: event selection, search region optimization, fitting procedures

The Earth Limb: Background & Control Sample



Sky Survey Mode, θ_{rock} = 52°
Limb at θ_{rz} = 112°

Limb: θ_i > 60°

Data Selection

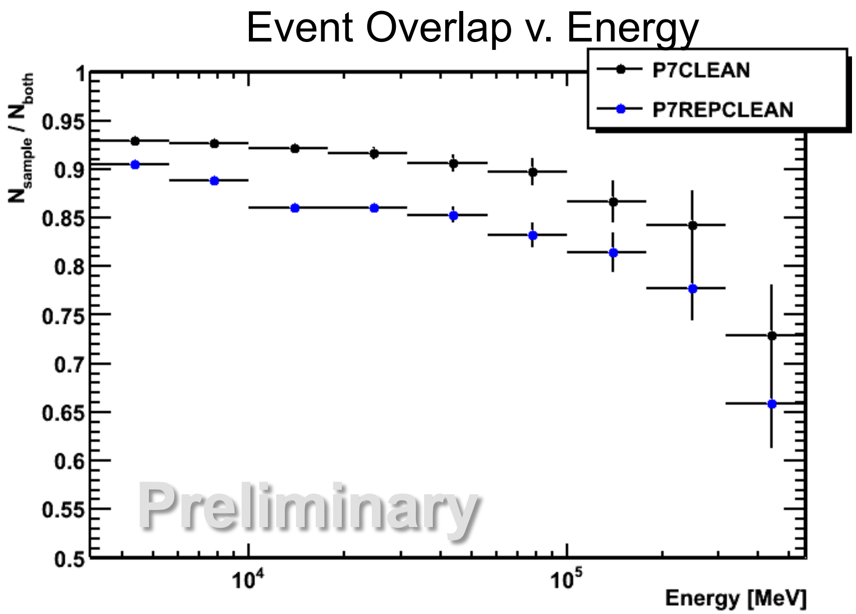
Parameter	Galactic data	Limb data
Observation Period	2008 August 4 – 2012 April 4	2008 August 4 – 2012 October 6
Mission Elapsed Time (s)	[239557447, 356434906]	[239557447, 371176784]
Energy range (GeV)	[2.6, 541]	[2.6, 541]
Zenith cut (°)	$\theta_z < 100$	$111 < \theta_z < 113$
Rocking angle cut (°) [a]	$\|\theta_r\| < 52$	$\|\theta_r\| > 52$
Data quality cut[b]	Yes	Yes
Source masking (see text)	Yes	No

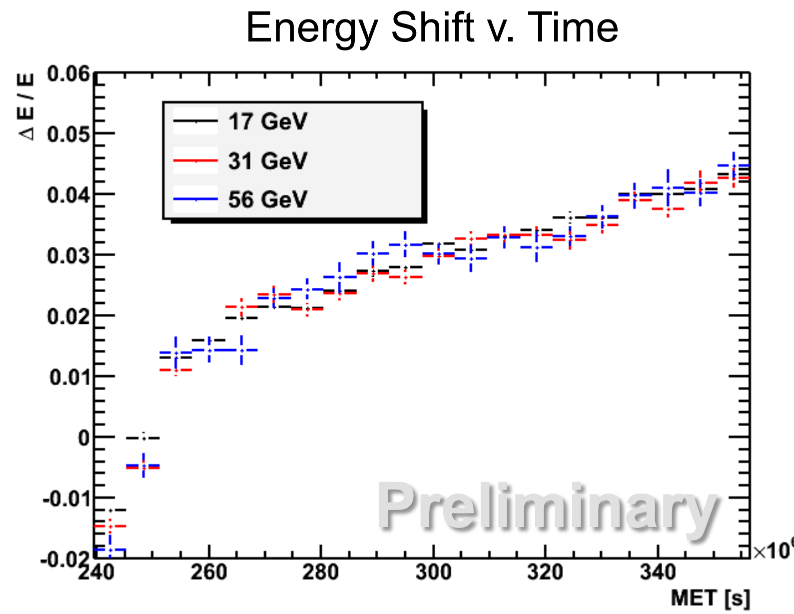
[a] Applied by selecting on `ROCK_ANGLE` in *gtmktime*.

[b] Standard data quality selection `DATA_QUAL == 1 && LAT_CONFIG == 1` in *gtmktime*.

- Search for γ-ray lines from 5 to 300 GeV using 3.7 years of flight data
- We use the **P7_REP_CLEAN** event selections
    - Same selection criteria, updated calibrations w.r.t. public **P7CLEAN**
    - Released to public once diffuse emission models / IRFs validated

Data Reprocessing with Updated Calibrations



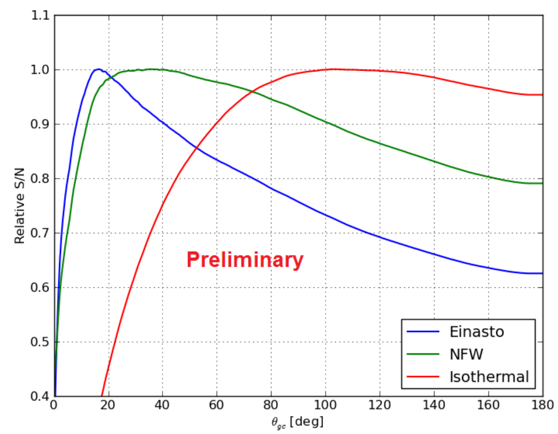


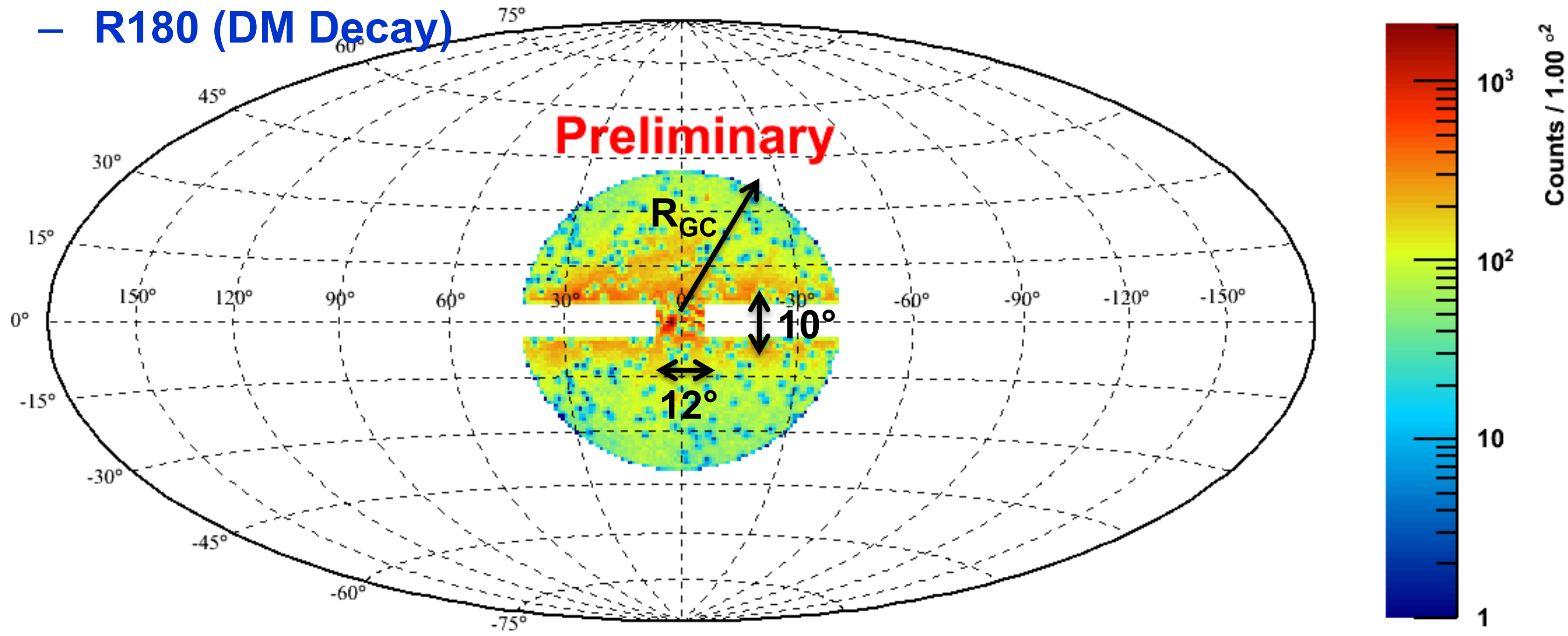
•Reprocessing Data with updated calibrations (primarily Calorimeter)
•Improves the agreement between the TKR direction and the CAL shower axis and centroid at high E, improving the direction resolution
•Corrects for loss in CAL light yield b/c of radiation damage (~4% in mission to date)
•80%+ overlap in events between original and reprocessed samples

Optimizing the Region of Interest (ROI)

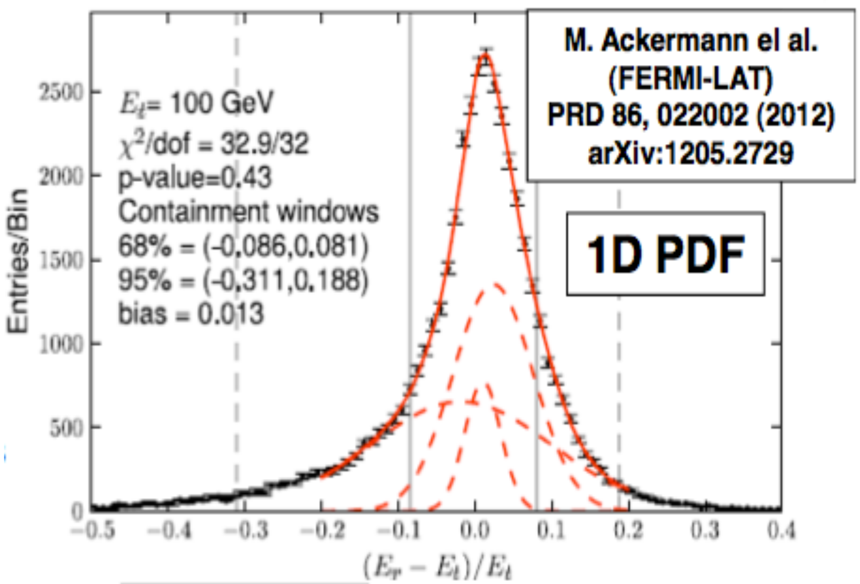
Optimize ROI for a variety of DM profiles
- Find R_{GC} that optimizes S/sqrt(B)

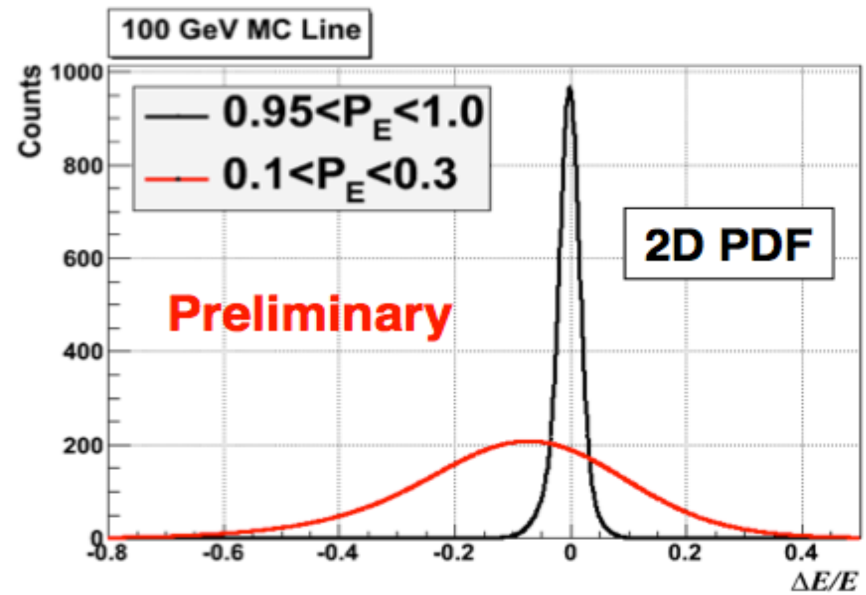
Search in 5 ROIs
- R3 (3° Circle)
- R16 (Einasto Optimized)
- R41 (NFW Optimized)
- R90 (Isothermal Optimized)
- R180 (DM Decay)





Improved Energy Resolution Model





- Updated analysis adds a 2nd dimension to line model: P_E.
  - P_E is the probability that measured energy is close to the true energy.
- "2D PDF" (a function of both energy and P_E).
  - Break Line into 10 P_E slices and fit triple Gaussian in each slice.
- Similar to public IRF description, which uses $\cos\theta$ instead of P_E
- Including $P_E \rightarrow$ ~15% improvement to signal sensitivity (when there is signal) and counts upper limit (when there is no signal).

Improved "2D" PDF for Line Search

Predicted Spectrum — Signal Model — Background Model

$$C(E', P_{\rm E}|\vec{\alpha}) = n_{\rm sig} D_{\rm eff}(E', P_{\rm E}|E_\gamma) w_{\rm sig}(P_{\rm E}) + \frac{n_{\rm bkg}}{c_{\rm bkg}} \left(\frac{E'}{E_0}\right)^{-\Gamma_{\rm bkg}} \eta(E') w_{\rm bkg}(P_{\rm E})$$

$$D_{\rm eff}(E'; E_\gamma) = \int^{FoV} \int^{ROI} D(E'; \theta|E_\gamma) \frac{I_{\rm sig}(\hat{p})\mathcal{E}(\hat{p}, \theta, E_\gamma)}{n_{\rm sig}} d\Omega d\Omega_{\hat{v}}$$

Effective Energy Dispersion

$$\eta(E') = \int^{FoV} \int^{ROI} \frac{I_{\rm bkg}(\hat{p})\mathcal{E}(\hat{p}, \theta, E_\gamma)}{n_{\rm bkg}} d\Omega d\Omega_{\hat{v}}$$

Effective Area Corrections

Including P_E in energy dispersion model:

- Include distributions of P_E for signal, $w_{sig}(P_E)$, and background, $w_{bkg}(P_E)$ in PDF.
- Take both from flight data for entire ROI & energy fit window.
- Fit for Γ_{bkg}, n_{sig}, n_{bkg}
- c_{bkg} is given by normalization of background model

Test Statistic, Significance & Trials Factors

Test Statistic (TS) and local significance (s_{local}) given by ratio of likelihood of best fit to null hypothesis:

$$TS = 2\ln\frac{\mathcal{L}(n_{\rm sig} = n_{\rm sig,best})}{\mathcal{L}(n_{\rm sig} = 0)}$$

$$s_{\rm local} = \sqrt{TS}$$

Estimate trials factor using method of Gross & Vitells

- See [arXiv:1005.1891v3] and [arXiv:1105.4355v1]

Systematics: instrumental and methodological uncertainties

Three Types of Systematic Uncertainties

Uncertainties that affect the conversion from n_{sig} to $\Phi_{\gamma\gamma}$

- E.g., exposure, express as $\delta\varepsilon/\varepsilon$
- Do not affect fit significance

Uncertainties that scale n_{sig}

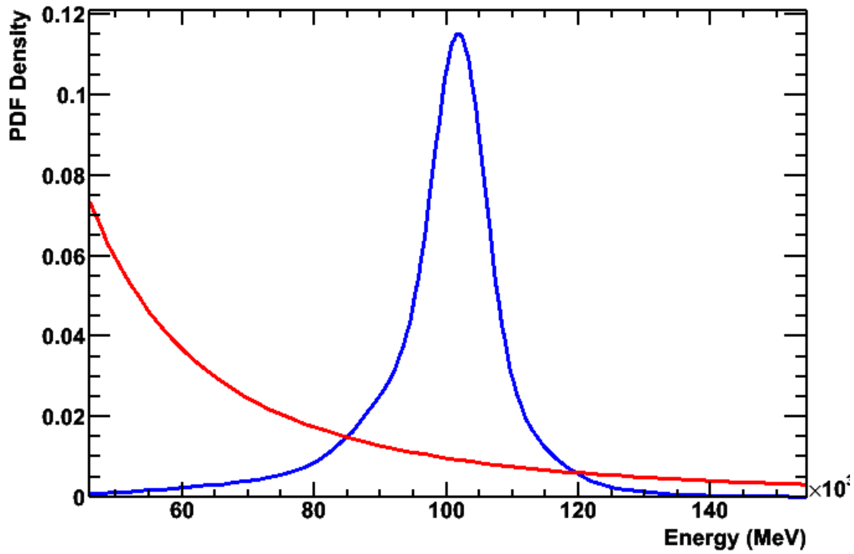
- E.g., modeling energy dispersion, express as $\delta n_{sig}/n_{sig}$
- Affect significance, but will not induce false signals

Uncertainties that induce or mask a signal

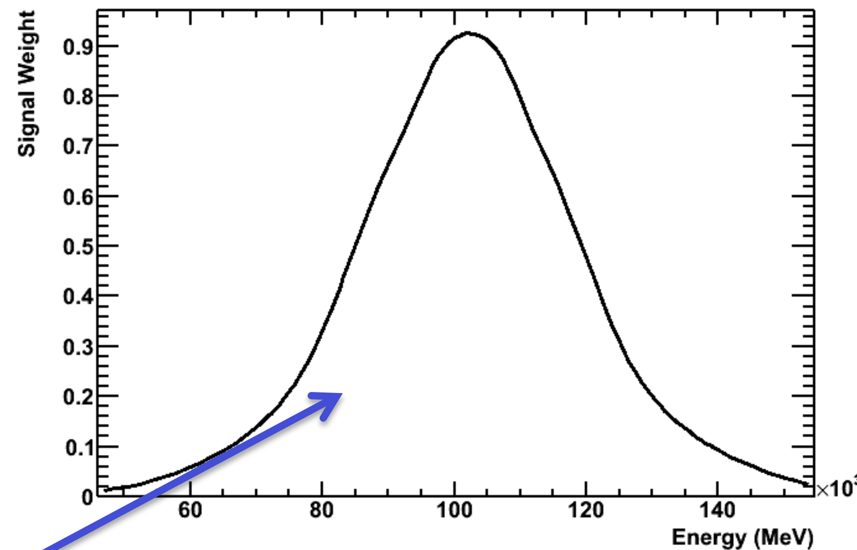
- Express as uncertainty in fractional signal, δf

“Effective Background”

Signal and Bkg. PDFs



Signal Weight v. Energy



$$b_{eff} = N \int \boxed{\frac{C_{\rm sig}(E')}{C_{\rm sig}(E') + C_{\rm bkg}(E')}} dE'$$

$$f = \frac{n_{\rm sig}}{b_{\rm eff}} \simeq \frac{s^2_{\rm local}}{n_{\rm sig}}$$

•To consider instruments effects it is useful to look at the potentially induced fractional residual (f, i.e., the Signal-to-noise ratio).

•It is important to consider only the background “under” the signal peak ($b_{\rm eff}$).

Uncertainties of $\delta\varepsilon/\varepsilon$

Exposure variation across ROI

- Depends on ROI, from <1% (R3) to ~14% (R180)
- Can be removed by re-calculating J-factors for specific DM model

Uncertainty of A_{eff} scale

- Estimated at 10% for consistency checks on flight data

These are smaller than the typical statistical variation on the upper limits which are typically ~50%.

Uncertainties of $\delta n_{sig}/n_{sig}$

Fit energy grid spacing

- 0.5 σ_E steps would miss at most 10% of signal

Energy resolution

- From CERN beam-test we estimate energy resolution know to 10%
- MC studies show that this yields $\delta n_{sig}/n_{sig} = 7\%$
- Also applicable to intrinsic broadening (e.g., from $Z^0\gamma$)

P_E distribution variation

- Varying P_E gives $\delta n_{sig}/n_{sig} = 1\%$

Energy dispersion model θ-variation

- Varying θ distribtuion gives $\delta n_{sig}/n_{sig} = 2\%$

•These are smaller than the typical statistical variation.
•For a 5σ signal the systematic uncertainty would be 0.6σ, as compared to the expected statistical variation of 1σ.

Uncertainties of δf

Cosmic-ray Contamination

– Reasonably small ($\delta f < 1.5\%$) for P7_REP_CLEAN class

Astrophysical Background Modeling

– Scanning many ROIs & energy and looking at the distribution of significances to quantify non-random behavior

– Simulating data with a broken power-law, and fitting for a line at the break energy

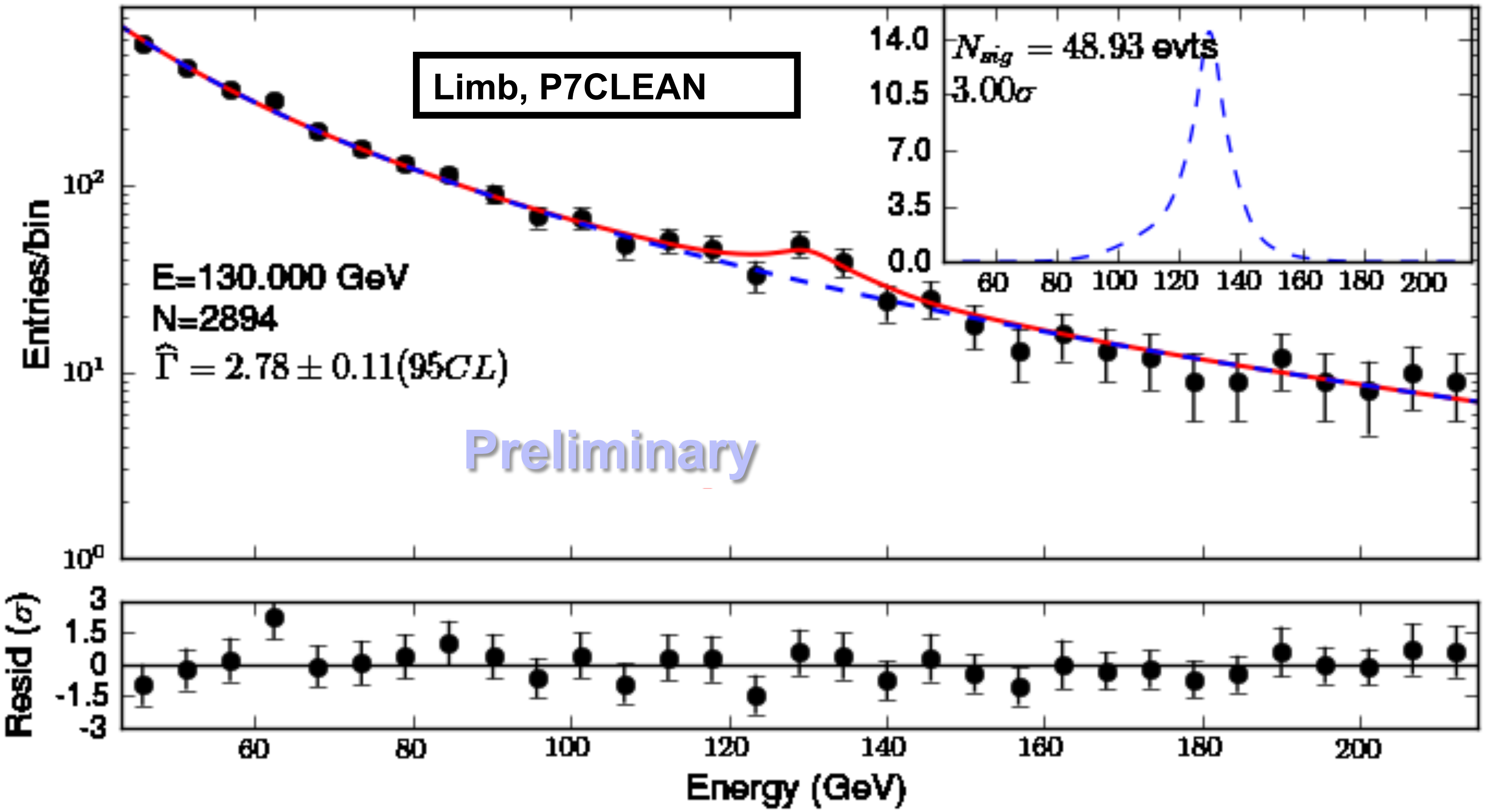
– Both give $\delta f \sim 2\text{-}3\%$

Checks of control regions

– Earth Limb & Galactic plane generally smooth $\delta f \sim 2\text{-}3\%$

– However…

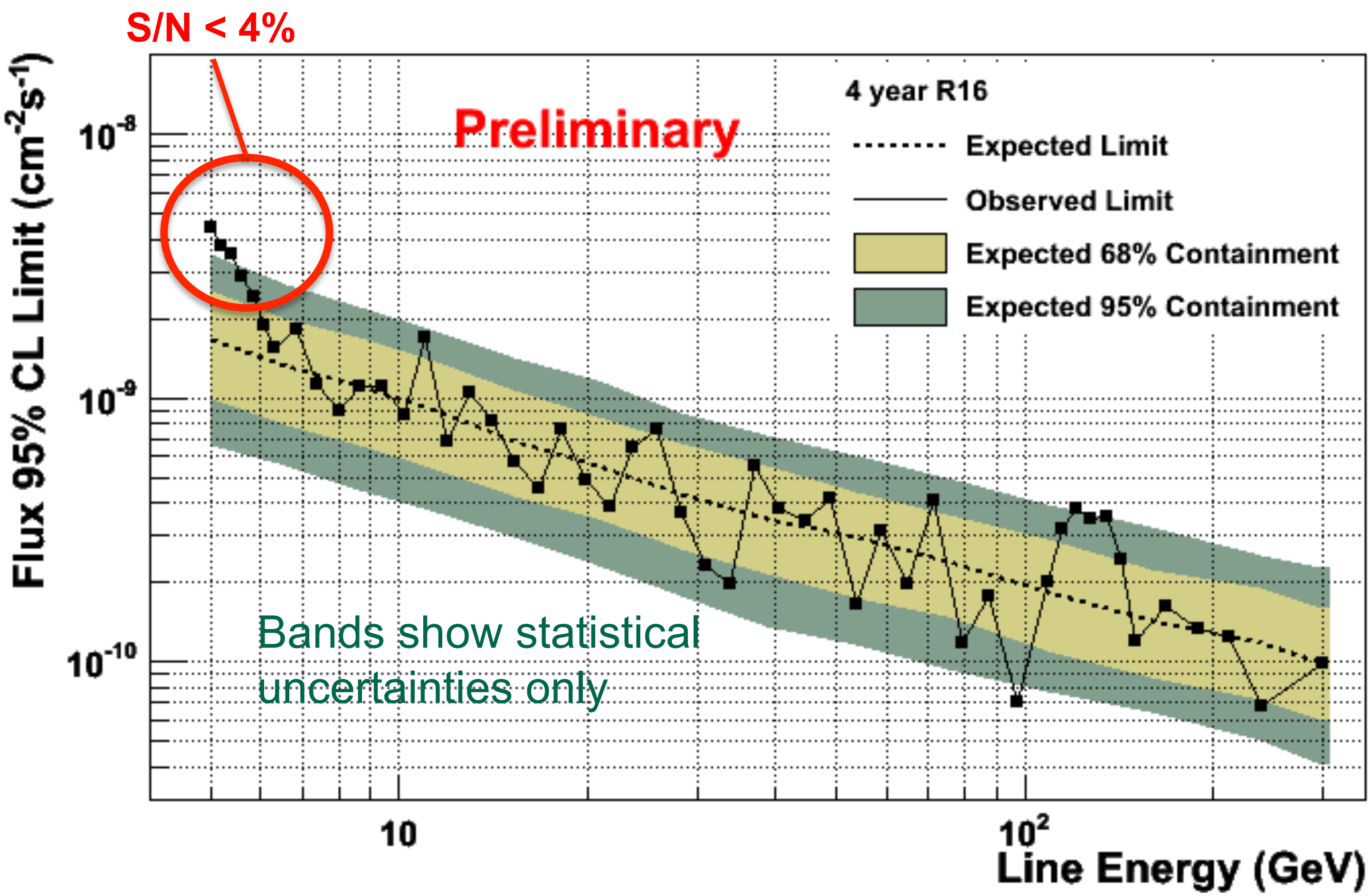
Fitting the Earth Limb



•Fit to Earth Limb data results in a 3.0σ signal, with a fractional residual of f~20%
•Reduced to 2.0σ (f=14%) in P7_REP_CLEAN data

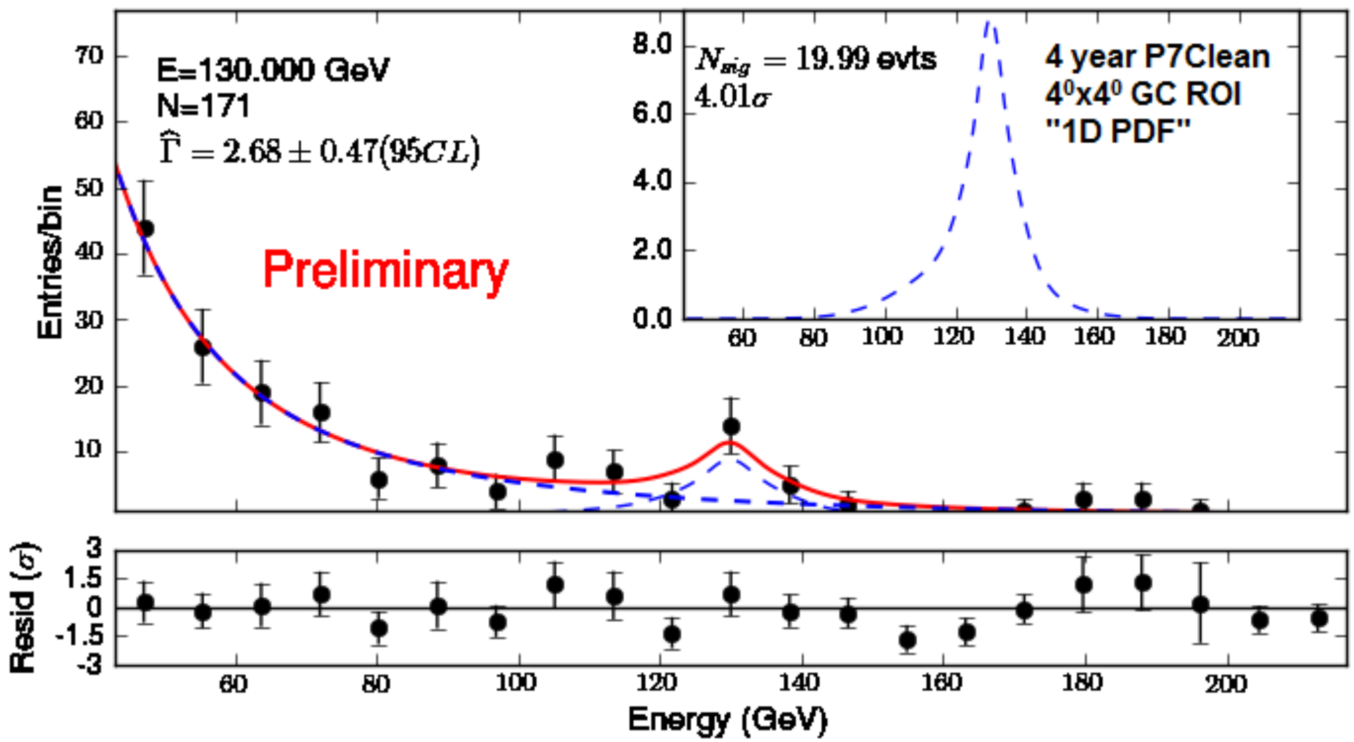
Results

Fermi-LAT Line Search Flux Upper Limits



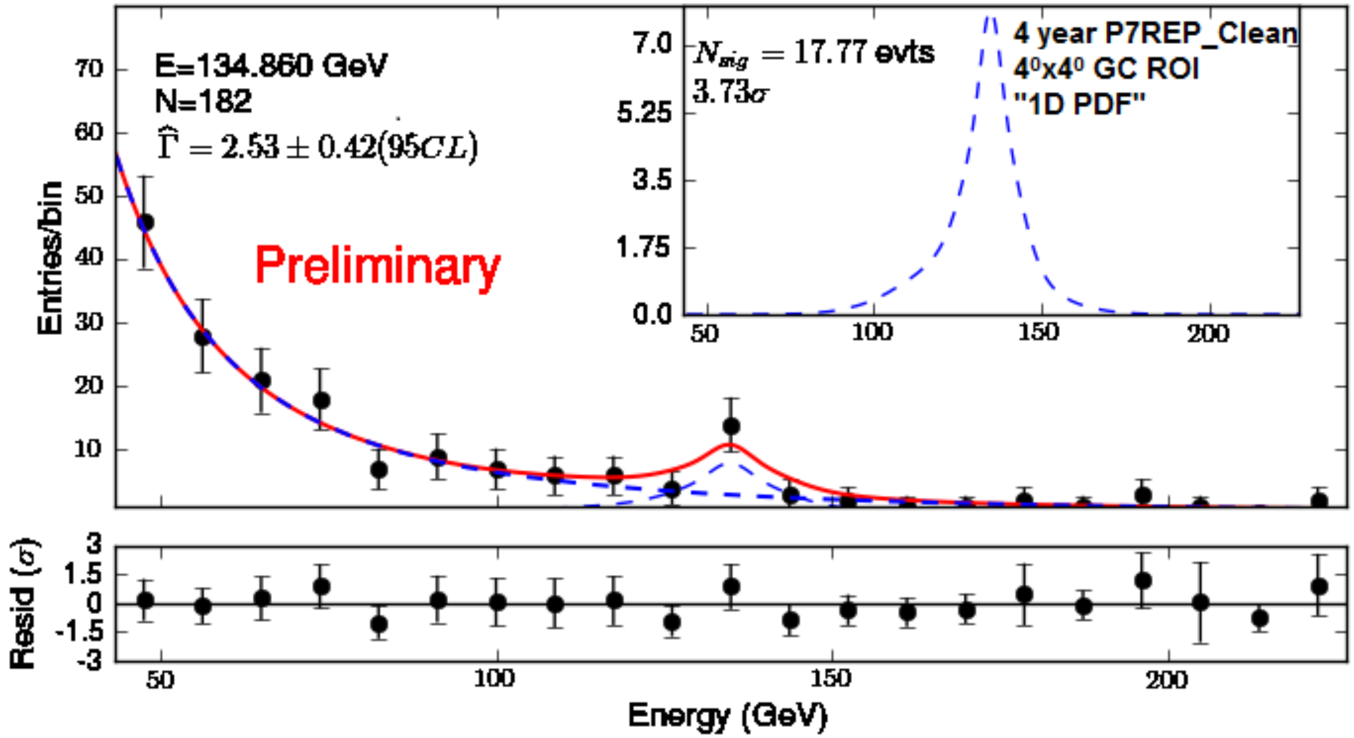
- Most of the limits fall within the expected bands.
- Near 135 GeV the limits are near or slightly above the upper edge of the bands.
- The excess at low energies is within systematic uncertainties.

Fermi-LAT Team Line Search at 135 GeV



- 4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data
    - Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)

Fermi-LAT Team Line Search at 135 GeV



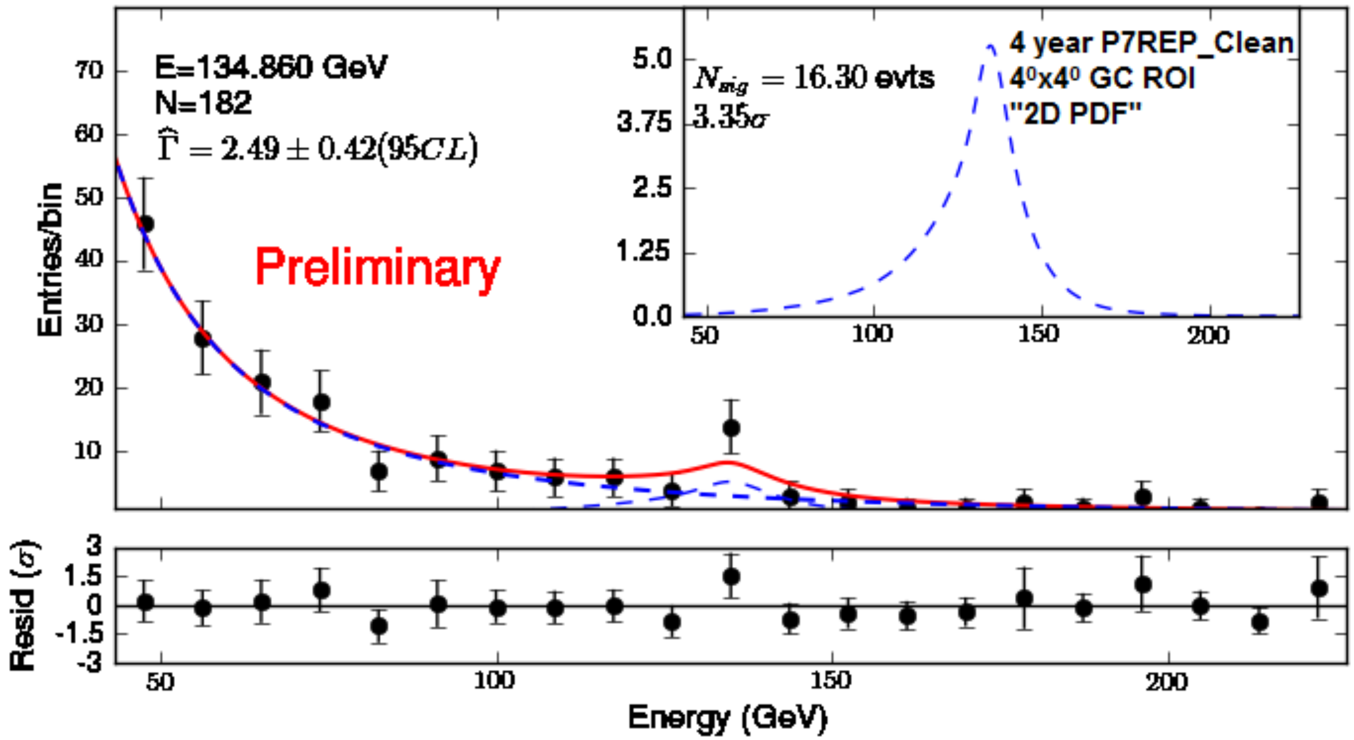
•4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data

•Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)

•3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data

•Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)

Fermi-LAT Team Line Search at 135 GeV

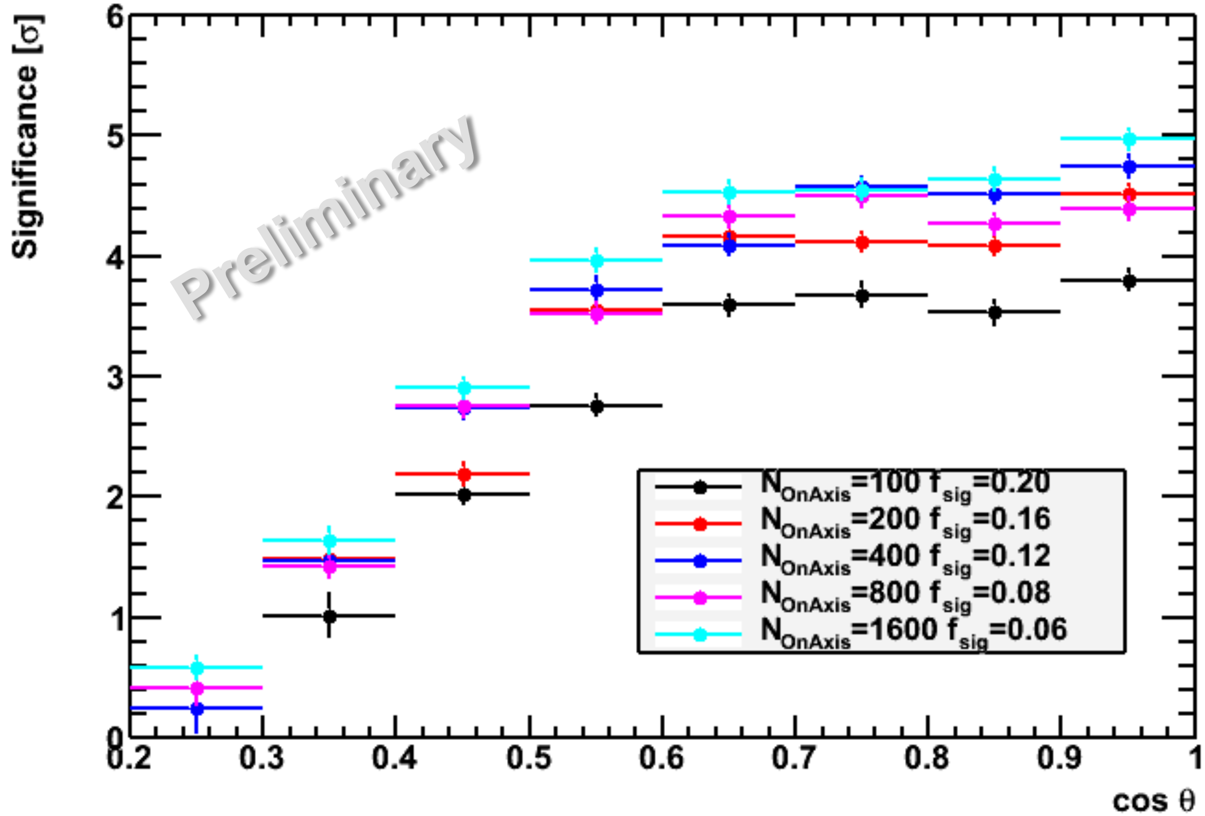


- 4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data
  - Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)
- 3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)
- **3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data**
  - **Look in 4°x4°GC ROI, Use 2D PDF (P_E in data)**
  - **<2σ global significance after trials factor**

New and Upcoming Developments

Modified Observing Strategy?

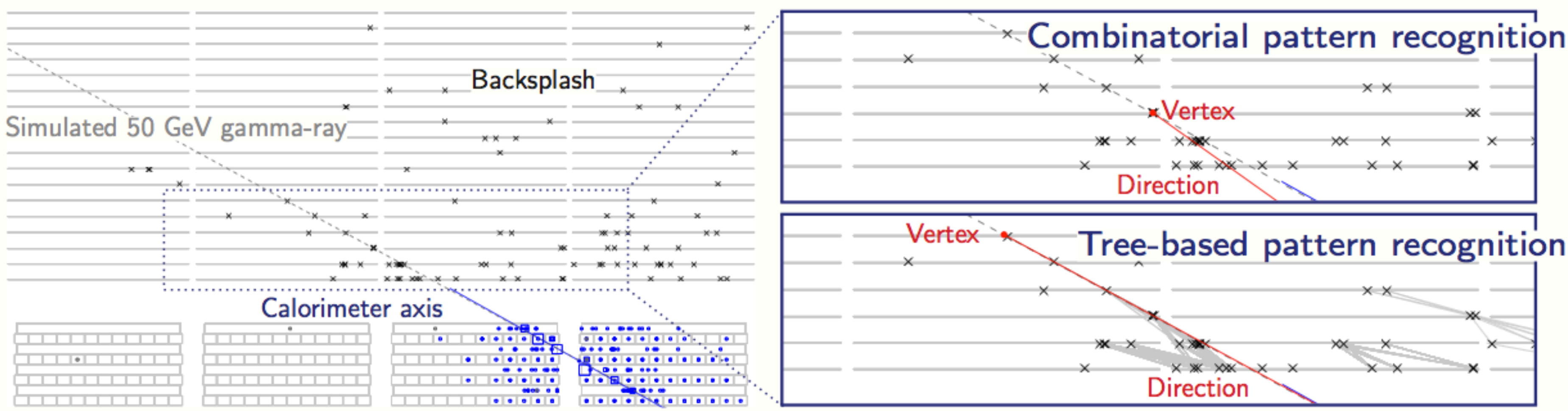
Simulated Sensitivity to 130GeV Line as a Function of θ



•Toy MC simulations of sensitivity to a 130GeV line for a range of signal-to-noise ratios favor energy resolution over A_{eff} slightly more than naïve scaling predictions.

Out to about θ=50°, the improving energy resolution balances out the decreasing A_{eff}. Less sensitivity past θ=60°.

Pass 8 Event Reconstruction



•Improved TKR and CAL reconstruction algorithms mitigate issues with CAL /TKR agreement, help avoid features in A_{eff} curve.

•Expect ~25% increase in acceptance above ~10 GeV from using improved reconstruction information for event selection.

•Expect better energy resolution at high energies from improved shower profile fitting.

Pass 8 event analysis, nearing completion (expected in 2013) will improve our prospects for answering questions about the spectral feature at 130 GeV.

130 GeV Line Summary

Spectral feature at 130 GeV near the GC is a potentially interesting hint of DM annihilation

- Fractional residual up to 60% in 4°x4° box around GC
- Not caused by background contamination

Similar feature seen in the Earth Limb and may be attributable to dips in efficiency at energies just above and below 130 GeV

- The Earth Limb features could explain between 30%-50% depending on the ROI under consideration.

Data have been reprocessed with updated CAL calibrations and analyzed with improved “2D” energy dispersion model

- Signal significance has fallen w.r.t. previous analysis
  - s_{local} 4.1σ -> ~3.35σ: still consistent w/ Weniger (2012)
- Feature energy increased to ~135 GeV

Too soon for definitive statements

SUMMARY

Summary

Fermi-LAT is optimized for many types of data analysis

- This is paying off with great science in several area
- Several breakthroughs in the last year have been synthesis studies
  - Building on catalogs, MW observations, analysis improvements

Many strategies for DM searches

- No clear signals, but several features warranting more investigation
  - 130 GeV persists, but significant doubts remain

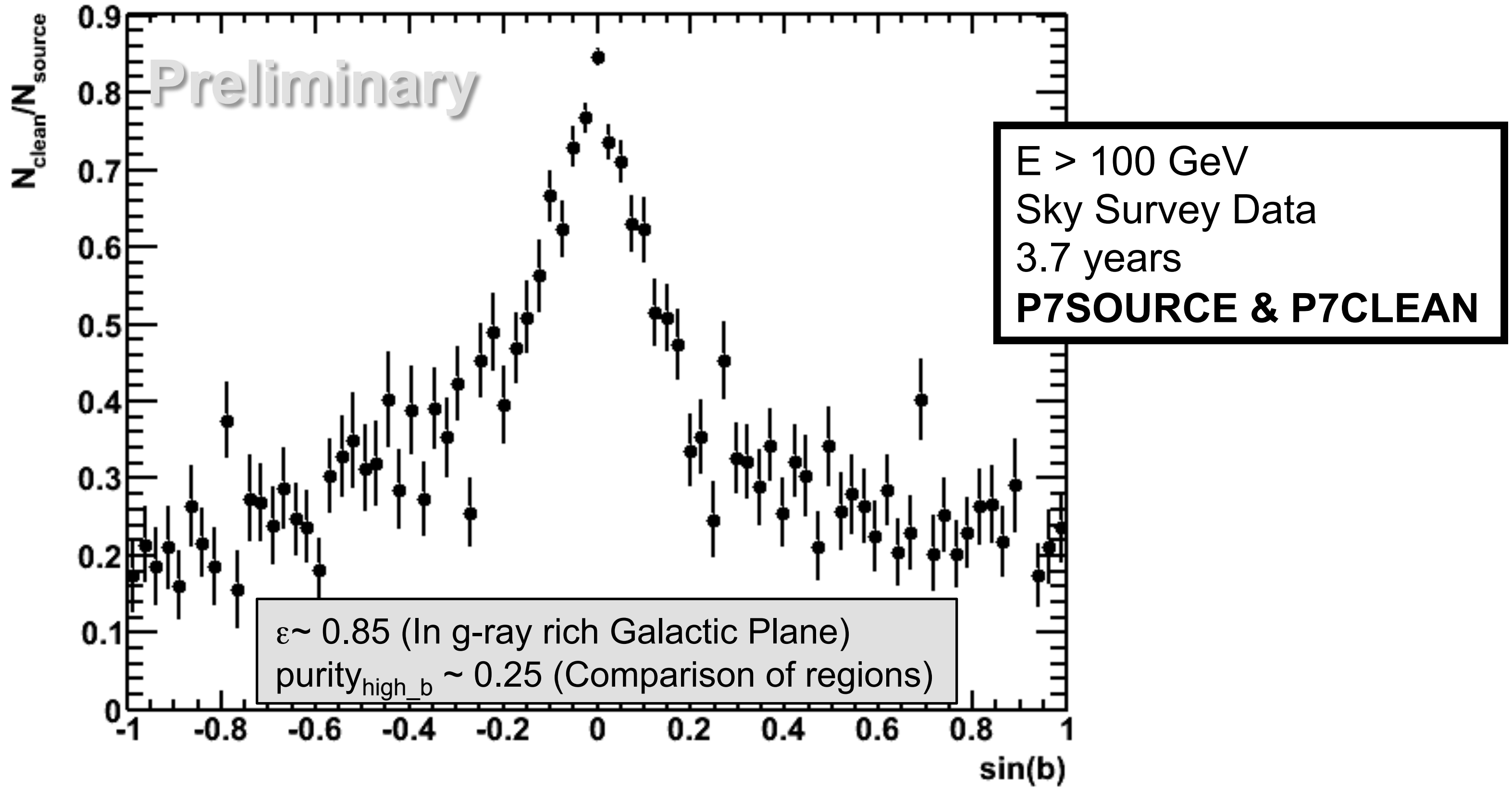
Ongoing improvements to all analysis components: event-section, IRFs, diffuse models, analysis tools

- See for yourself. Data, tools and many helpful people are available at http://fermi.gsfc.nasa.gov/ssc/

EXTRA SLIDES

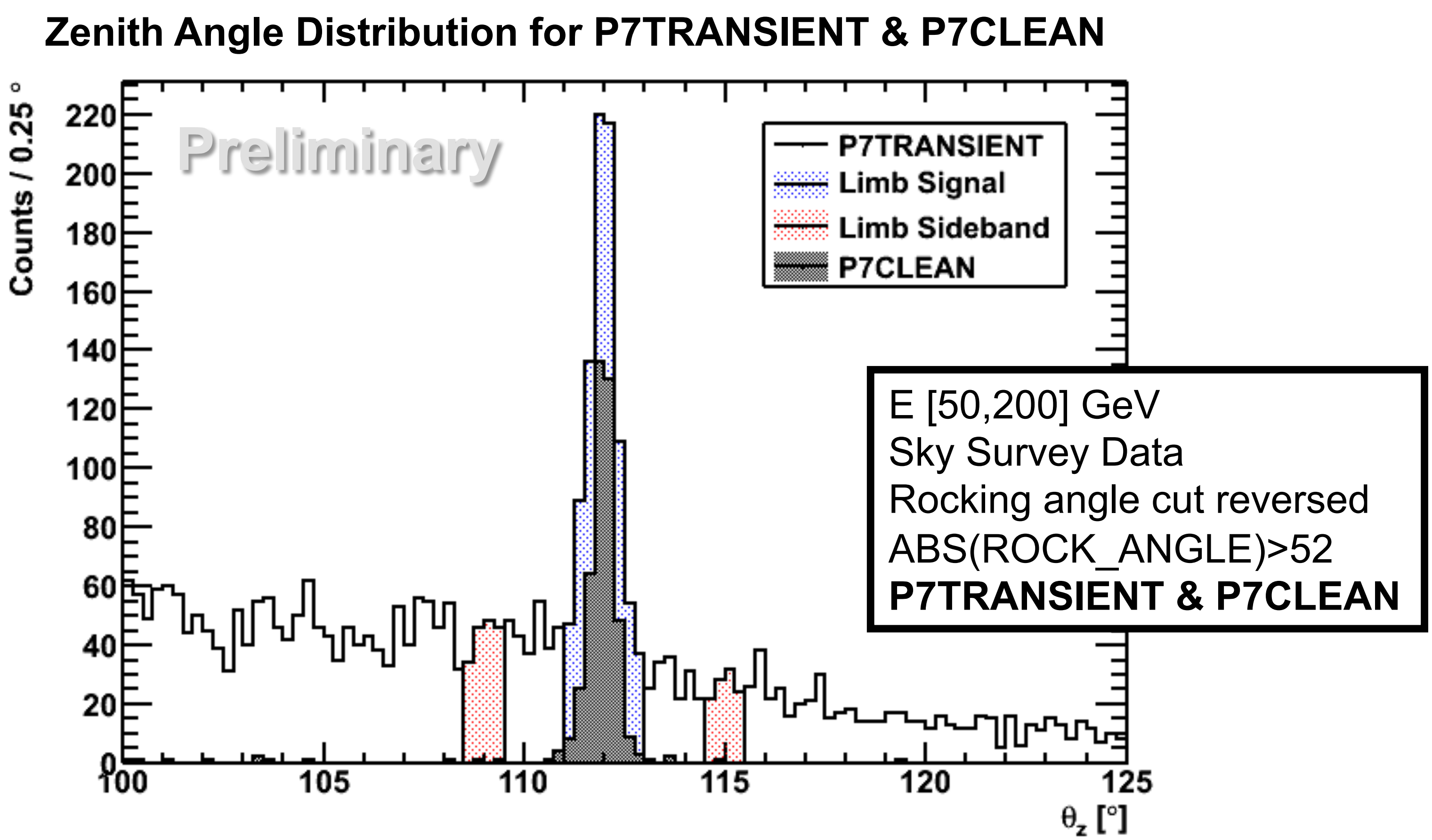
Cosmic-ray Background Contamination

Fraction of P7CLEAN events in P7SOURCE. vs. Gal. Lat.



- Above 100 GeV many high-latitude events in P7SOURCE & ! P7CLEAN are not γ rays.
- CR-background reconstructed as γ rays will show a variety of spectral features, which can corrupt and compromise the sideband fit as well as induce fake signals.
- The effect of residual contamination in P7CLEAN is small for large ROI (δf=0.014 for R180) and is **negligible** for smaller ROI near the GC (δf < 0.01 for R3)

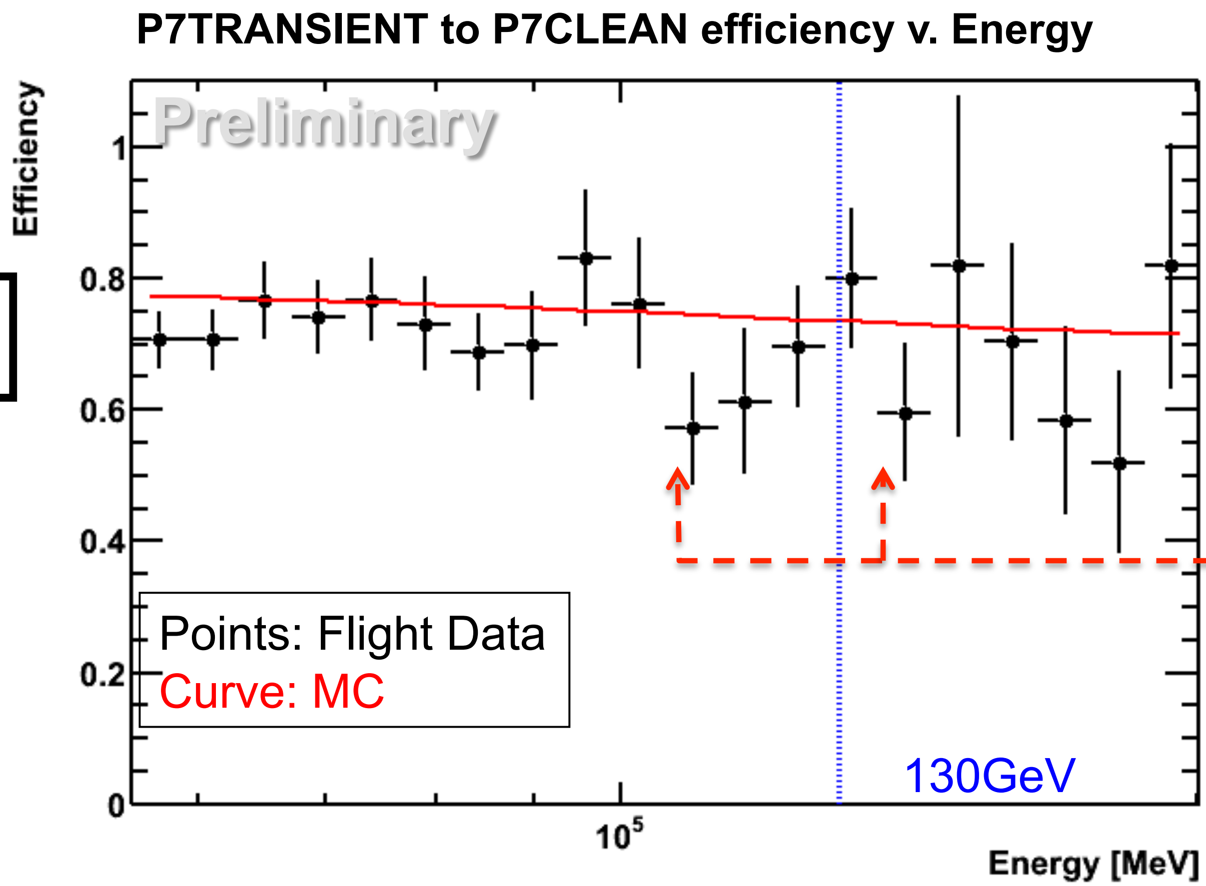
Measuring Efficiency with the Earth Limb



- The Earth Limb is unique in that it can be seen in the loose P7TRANSIENT event class at high energies.
- This allows us to use it to measure efficiencies for tighter event classes as a function of energy.

P7TRANSIENT to P7CLEAN Efficiency

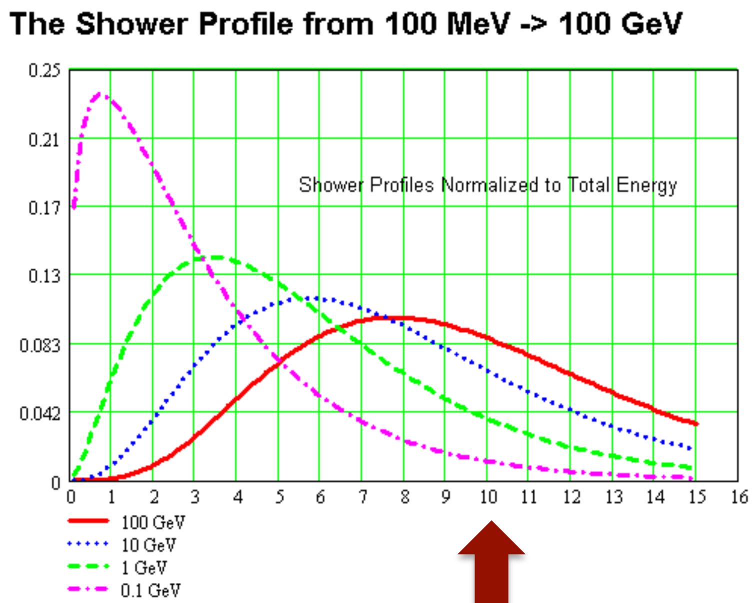
Same data as previous slide



These dips in efficiency appear to be related to the CAL-TRK agreement.

- The efficiency at ~115Gev is 0.57/0.75 = 75% of the MC prediction.
- This would cause something < 30% boost in signal at 130 GeV relative to the prediction from nearby energy bins.

θ-Dependence of Energy Resolution



Total LAT depth on axis = 10.1 X_0

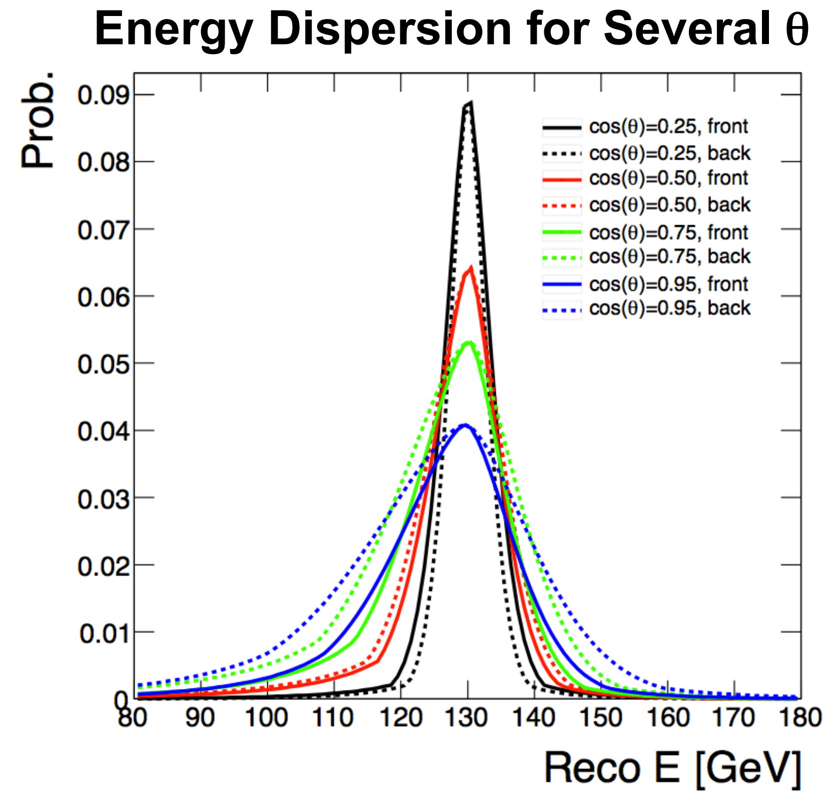
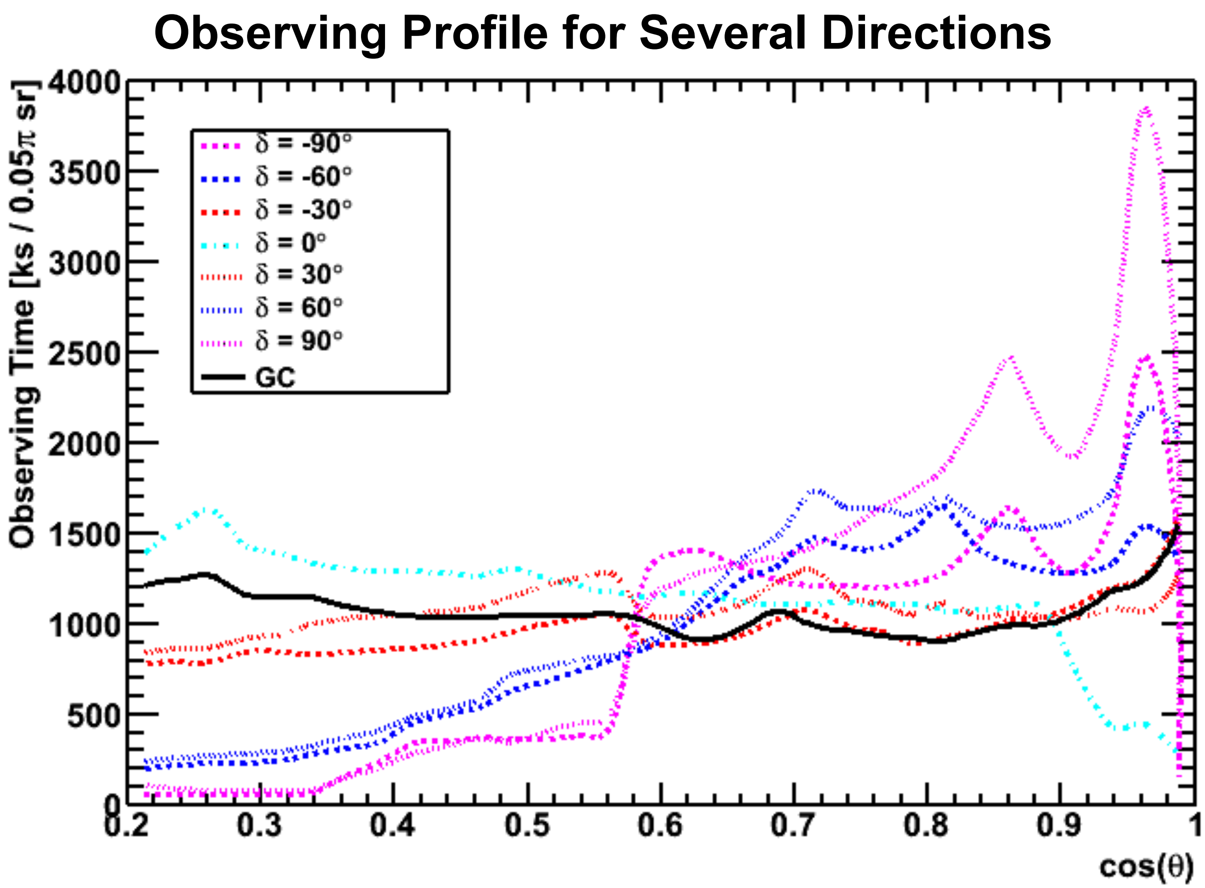


Fig. from Whiteson JCAP11(2012)008 [arXiv:1208.3677v2]. Made using Fermi-LAT *ScienceTools* energy dispersion parameterization for P7CLEAN_V6 event class.

At high energies (>10GeV) EM showers are not fully contained.
The Energy resolution improves off-axis as the projection effect increases the containment fraction.

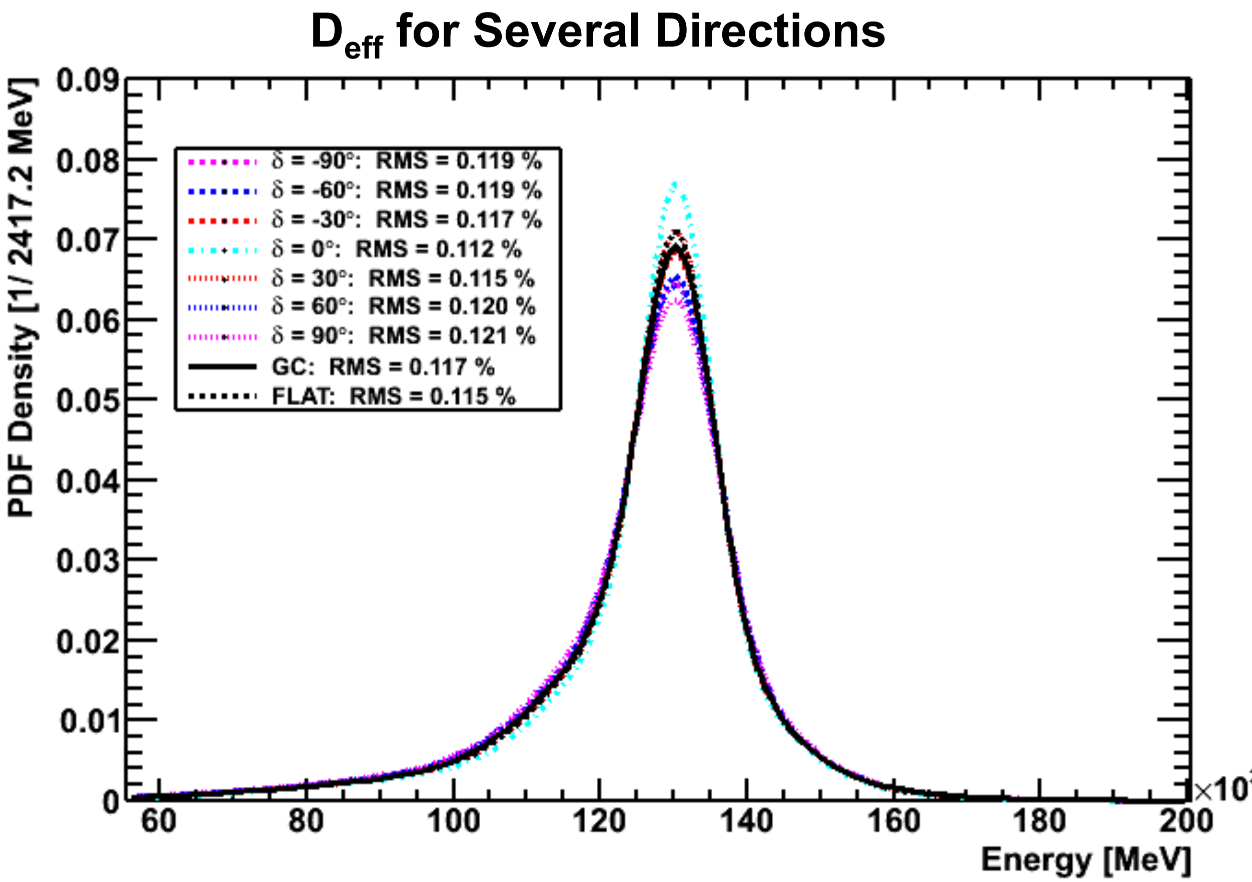
Observing Profiles Variations



•Averaged over years, the observing profile depends primarily on the DEC of the Region of Interest (ROI).

•The Galactic Center gets somewhat more time right on-axis than other sources (and less time slightly off-axis). This is because $DEC_{GC} \sim Inclination_{orbit}$

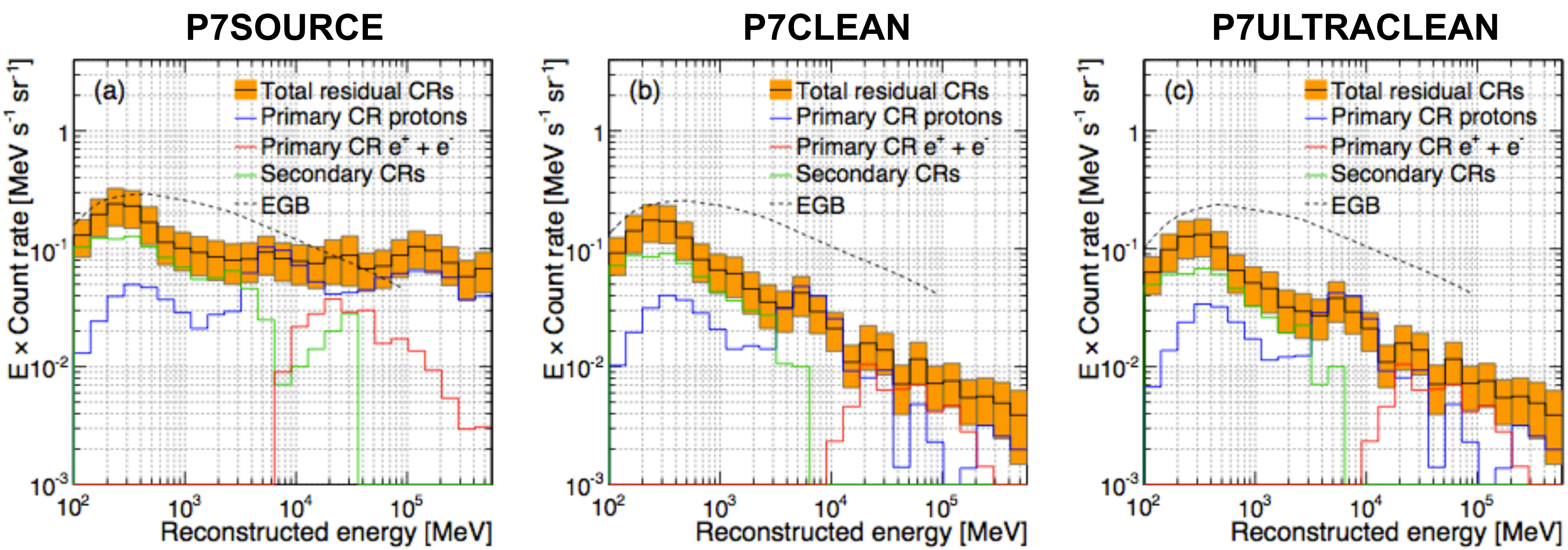
θ-averaged Energy Resolution by Declination



•The θ-averaged D_{eff} weighted for observing profile varies moderately with declination (δ).

•Using the wrong profile will not induce a signal, but can scale the n_{sig} and the significance of a signal by up 25%.

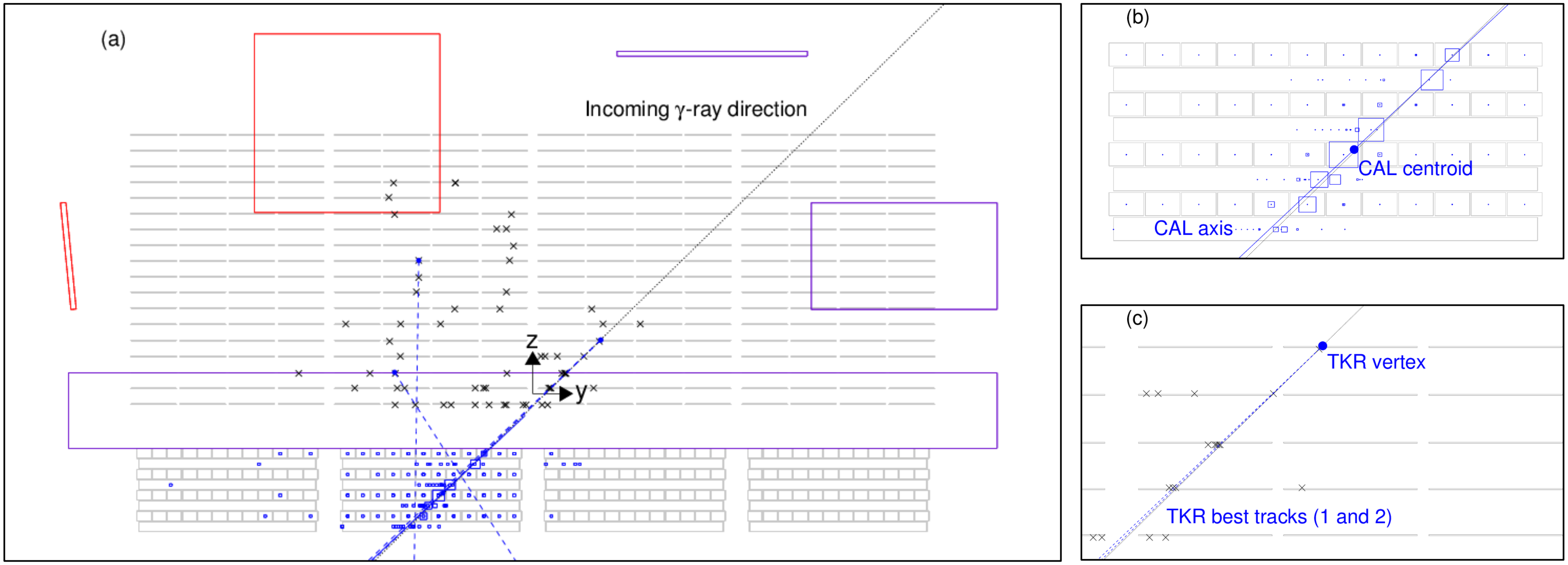
Background Contamination Rates



ApJS, 203, 4. [arXiv:1206.1896]

- Comparing P7SOURCE fits for small ROI in the galactic plane to large ROI where the P7SOURCE class is dominated by CR background is dangerous.
- The effect of residual contamination in P7CLEAN is small for large ROI ($\delta f=0.014$ for R180) and is **negligible** for smaller ROI near the GC ($\delta f < 0.01$ for R3)

CAL/TKR Agreement, High Energy PSF, etc..



- CalTrackAngle: angle between CAL axis and TKR direction
- CalTrackDoca: Distance of Closest Approach (DOCA) between track and CAL centroid
- P_{CORE}: Probability that event is within the CORE of the PSF

- Above ~10GeV the backsplash from the CAL causes many hits in the TKR and increases the probability of picking the wrong hit for a track and pulling the track direction well into the tails of the PSF.
- We use the TKR /CAL agreement to mitigate this and also to reduce CR background.

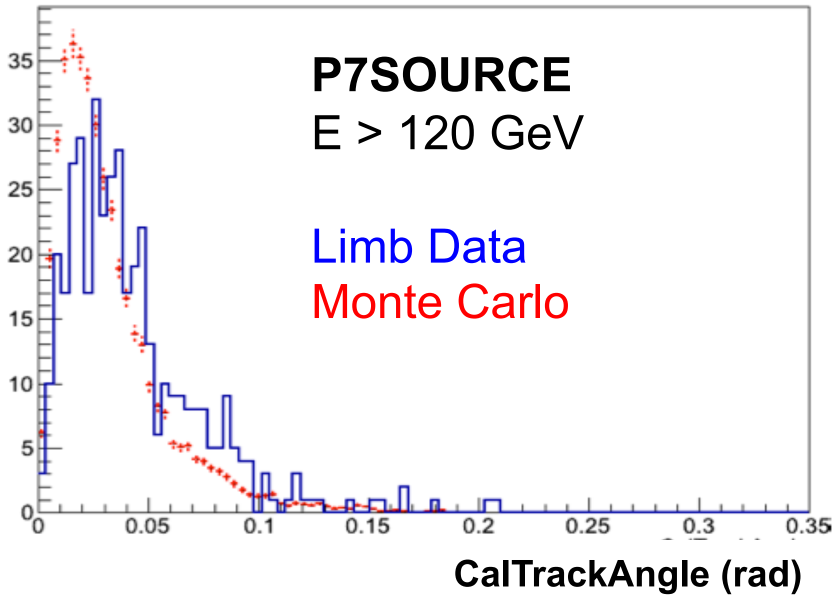
Event Selection Cuts

Selection	CUT	Comments
P7TRANSIENT	Quality Cuts	
	Charged Particle Veto Analysis	
	Loose cut on P_{all} (0.2)	Small feature in MC (S/N ~0.05)
P7SOURCE	CAL & TKR Vetos	
	Reject MIPs with CAL & TKR	
	CAL / TKR Agreement	
	PSF Quality	Depends on CAL/TKR agreement
	Tight cut on P_{all} (0.996 at 130GeV)	Depends on CAL/TKR agreement
P7CLEAN	Reject MIPs, but lose A_{eff}	
	Shape of event in CAL	
P7ULTRACLEAN	Tighter cut on P_{all} below 10GeV	

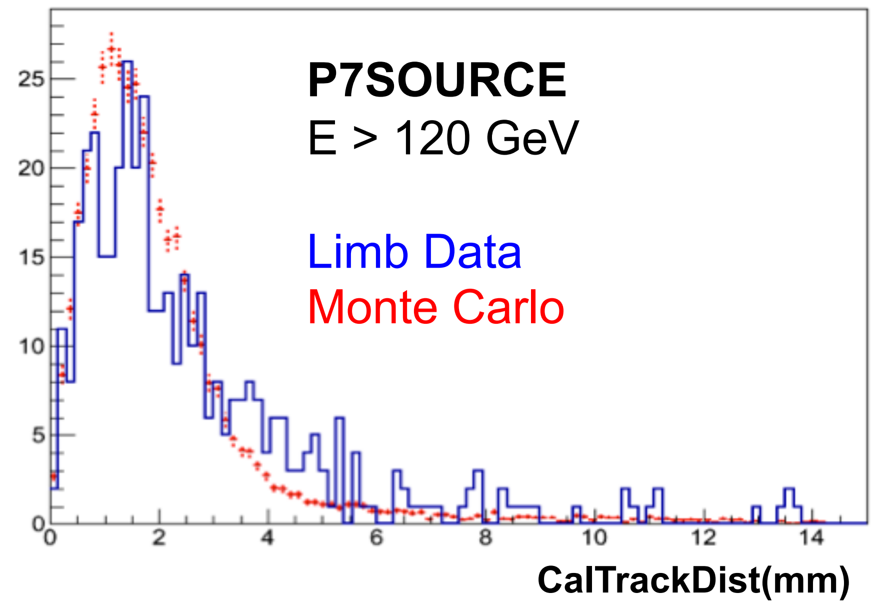
The two cuts in red appear to account for most of the difference between Earth Limb data and MC at high energies.

Data / Monte Carlo Comparisons

Angle Between TKR and CAL Axis



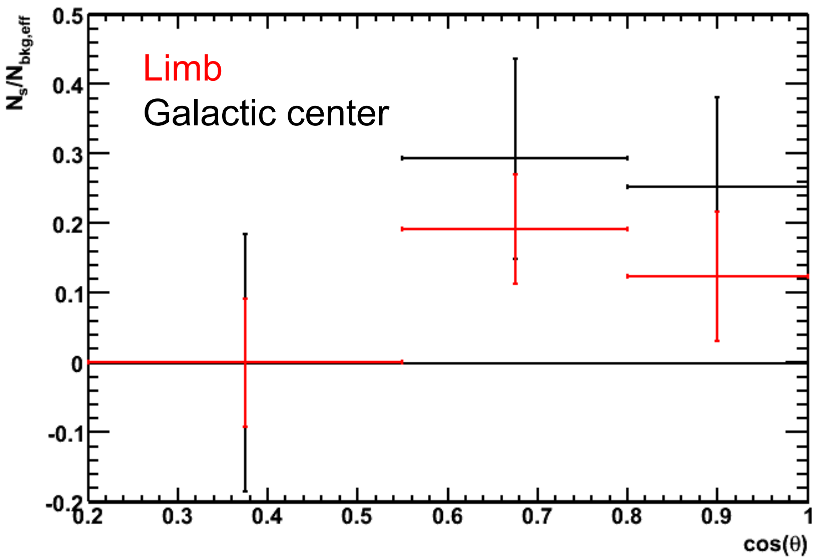
Distance between TKR and CAL Centroid



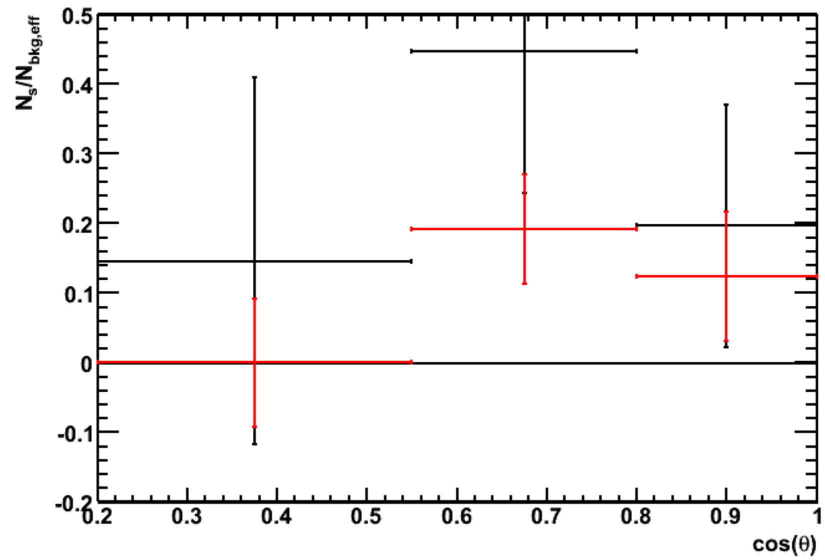
- Detailed comparisons between flight data and Monte Carlo simulations show that the CAL/TKR agreement is somewhat worse in the flight data than in the simulations.
    - Improved with reprocessed data
- These two variables are among the most important in the Classification Tree analyses used for event selection and classification.

Signal to Noise of Excess as a function of θ

12°x12° box around GC



8°x8° box around GC



•Many people have noted that the spectral excess in both the the GC and the earth limb is largest near $\cos(\theta)=0.7$.

•By comparing the fractional residuals we see that the features in the Earth Limb could account for about 50% of the excess in a 12°x12° box around the GC, but only about a 30% of the excess in a smaller 8°x8° box where the feature is brighter.